Air
Force
Office
of
Scientific
Research

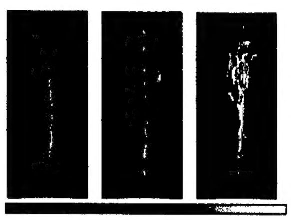
Final Report

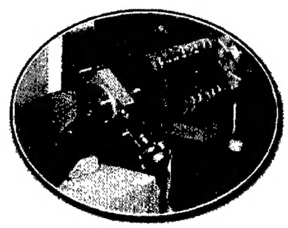
Multidisciplinary University Research Initiative Program

"High Energy Microwave Device Consortium"

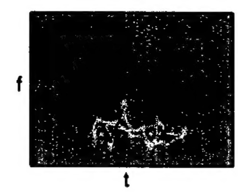
14 July 2000

The University of New Mexico





Time-frequency analysis of HPM sources.



microwave
sciences

AF OFFICE OF SCIENTIFIC RESEARCH

Central Consortium

Consortium Members: Texas Tech University, University of New Mexico, University of Michigan, and Microwave Sciences Inc.

Texas Tech University

REPORT DOCUMENTATION PAGE

AFRL-SR-BL-TR-00-

0399

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPOR
	14 July 2000	Final, 14 April, 1995 - 14 April,2000

4. TITLE AND SUBTITLE

TRI-UNIVERSITY, MULTIDISCIPLINARY, HIGH ENERGY, MICROWAVE DEVICE CONSORTIUM (MURI 94)

5. FUNDING NUMBERS

FQ 8671-9900761 (Start)
FQ 8671-0000674 (End)

6. AUTHOR(S)

M. Kristiansen (TTU), E. Schamiloglu (UNM), R. Gilgenbach (UM), and J. Benford (MSI)

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Texas Tech University
Pulsed Power Laboratory
Department of Electrical Engineering
P.O. Box 43102
Lubbock, TX 79409-3102

8. PERFORMING ORGANIZATION REPORT NUMBER

AFOSR MURI 2000-6

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Dr. Robert Barker
Directorate of Physics & Electronics
AFOSR/NE
801 North Randolph Street, Room 732
Arlington, VA 22203-1977

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

F49620-95-1-0333

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release, distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

The AFOSR MURI High Power Microwave program was instituted in April 1995. This report covers activities conducted by the MURI Central Consortium from April 15, 1995 – April 14, 2000. The consortium was composed of faculty members and students from Texas Tech University (Coordinating University), The University of New Mexico, and The University of Michigan. Microwave Sciences, Inc. is an industrial partner. The participants come from Electrical Engineering, Physics, Materials Science, Computational Systems, and Nuclear Engineering. The research at each university complements each other and covers Vircators, High Efficiency Backward Wave Oscillators, Fast Wave Gyro Devices, Plasma Filled Devices, Ferroelectric Cathodes, Mode Converters, Ultra Wideband Technology, and Microwave Vacuum and Window Breakdown. The overall emphasis of the proposed research was to increase the device efficiencies and to reduce their weight and volume. Efforts to increase the radio frequency, vacuum electric field strength of cavities and windows hold promise for higher energy density devices. Novel cathodes may lead to longer pulse devices resulting in higher energy sources. An important aspect of the program is to research various control strategies relevant to pulsed high power microwave sources. A list of journal and conference papers is attached showing progress on investigations during this contract period.

14. SUBJECT TERMS

High Power Microwaves, Sources, Breakdown, Pulse Shortening

15. NUMBER OF PAGES

106

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

U.S. Department of Defense/
Air Force Office of Scientific Research

Contract No. F49620-95-1-0333

Multidisciplinary University Research Initiative Program

"High Energy Microwave Device Consortium"

Final Report – 14 April 1995 to 14 April 2000

July 2000

Central Consortium

Texas Tech University
University of New Mexico
University of Michigan
and
Microwave Sciences, Inc.

TABLE OF CONTENTS

This section of the report is the Progress Report for the final contract period from 1 Sept. 1999 to contract expiration date, 14 April 2000. This last progress report is formatted as were all previous yearly progress reports.

INTRODUCTION

The Department of Defense with AFOSR as their contracting Agency awarded three Multi-disciplinary University Research Initiative (MURI) grants in the area of high power microwave sources in April 1995. These three consortia are:

1. University of California at Davis (Western Consortium) with
   University of California, Los Angeles,
   University of California, Berkeley,
   Stanford Linear Accelerator Center and
   Northrop Grumman.

2. Texas Tech University (Central Consortium) with
   The University of New Mexico,
   The University of Michigan, and
   Microwave Sciences, Inc.

3. University of Maryland (Eastern Consortium) with
   Cornell University and
   Communications & Power Industries

In this report, we describe the goals, operation, and the activities of the Central Consortium from August 14, 1995 through April 14, 2000. The current Principal Investigators at each institution are:

Texas Tech University:
Dept. of Electrical Engineering
P.O. Box 43102
Lubbock, TX 79409-3102

	Phone	Fax	E-Mail
M. Kristiansen	806/742-2224	806/742-1281	krisk@coe.ttu.edu
L. Hatfield	806/742-1250	" " "	marieb@coe.ttu.edu
H. Krompholz	806/742-1251	" " "	hermannk@coe.ttu.edu
J. Dickens.	806/742-1254	" " "	jdickens@coe.ttu.edu
A. Neuber	806/742-1250	" " "	aneuber@coe.ttu.edu

University of New Mexico:
Dept. of Electrical and Computer Engineering
Albuquerque, NM 87131

	Phone	Fax	E-Mail
E. Schamiloglu	505/277-4423	505/277-1439	edl@eece.unm.edu
C.T. Abdallah	505/277-0298	" " "	chaouki@eece.unm.edu
C.B. Fleddermann	505/277-5628	" " "	cbf@chtm.unm.edu

(C.B. Fleddermann resigned from this effort 5/14/99.)

University of Michigan:
Nuclear Engineering Department
2355 Bonistell Blvd.
Ann Arbor, MI 48109-2104

	Phone	Fax	E-Mail
R. Gilgenbach	313/763-1261	313/763-4540	rongilg@engin.umich.edu
Y.Y. Lau	313/764-5122	" " "	yylau@engin.umich.edu

Microwave Sciences, Inc.
1041 Los Arabis Lane
Lafayette, CA 94549

	Phone	Fax	E-Mail
J. Benford	510/577-7157	510/577-7283	jnbenford@earthlink.net

PERSONNEL AT TEXAS TECH UNIVERSITY

Professor M. (Kris) Kristiansen, Principal Investigator and Consortium Director

Task

1. **Microwave Vacuum and Window Breakdown**
   - Prof. Lynn L. Hatfield (directs laboratory research)
   - Prof. Hermann G. Krompholz (directs laboratory research)
   - Dr. James Dickens (conducts laboratory research)
     Microwave experiment design and modeling of microwave systems
   - Dr. Andreas Neuber (conducts laboratory research)
   - David Hemmert, Graduate Student in Electrical Engineering, graduated with MS degree in Physics in May 1998 and continues for Ph.D. degree

2. **Ultrawideband Microwave Generation**
   - Prof. M. Kristiansen (directs laboratory research)
   - Dr. James Dickens (conducts laboratory research)
   - Dr. John Mankowski (conducts laboratory research)
     Resigned and is now employed at Accurate Automation Corp., Chattanooga, Tennessee.
   - Cooperative studies with J. Lehr, AFRL, Phillips Site.

3. **Alternate Geometry Vircators**
   - Prof. M. Kristiansen and Prof. Lynn L. Hatfield (direct laboratory research)
   - Dr. W Jiang (conducts laboratory research). Now employed at Nagaoka University of Technology, Nagaoka, Japan.
   - Dr. Kevin Woolverton (completed Ph.D. in Electrical Engineering and employed by Intel Corp.).

4. **Theoretical Modeling of Interactions in Plasma Filled Microwave Generators**
   - Prof. O. Ishihara (directs simulation work) resigned and now employed at Yokohama National University, Yokohama, Japan.
   - Doug Young (completed Ph.D., on faculty at Mercer University)
   - The research support for this project was terminated in July 1999.

5. **Deflecting Extended Interaction Klystron**
   - Associate Prof. Klaus Zieher (directs laboratory research)
   - The research support for this project was terminated in July 1998.

PERSONNEL AT THE UNIVERSITY OF NEW MEXICO
Professor Edl Schamiloglu, Principal Investigator

Task

6. **Demonstration of a Gigawatt Level Smart Tube**
   - Prof. Chaouki Abdallah (directs "Smart Tube" controls research)
   - Prof. Edl Schamiloglu (directs laboratory and theoretical research)
   - Dr. Raymond Lemke (Sandia National Labs. under contract to Phillips Laboratory) (computational and theoretical support)
   - Vatche Soualian, M.S. student on control theory
   - Gregory Todd Park, M.S. student on experiment
   - Tony Peredo, undergraduate research assistant
   - Kelly Hahn, undergraduate research assistant

7. **Hybrid Hard Tube BWO**
   (AFOSR/MURI and DURIP'96, DURIP'97, and DURIP'99 awards)
   - Prof. Edl Schamiloglu (directs research)
   - Dr. Frank Hegeler (laser diagnostics and hybrid hard tube)
   - Prof. Chaouki Abdallah (signal analysis)

8. **Plasma-Filled BWO**
   - Prof. Edl Schamiloglu (directs experiment and theory)
   - Dr. Frank Hegeler (plasma-filled experiments)
   - Dr. Osamu Ishihara (Texas Tech., directs simulation)
   - Dr. Doug Young (Texas Tech, simulations) (now on faculty at Mercer University)
   - Prof. Tom Antonsen (U. of MD collaborator)
   - Dr. Yuval Carmel (U. of MD collaborator)
   - Dr. Tony Lin (UCLA collaborator)

9. **Ferroelectric Cathodes**
   - Prof. Charles Fleddermann (directs research)
   - Prof. Edl Schamiloglu
   - Dr. Frank Hegeler
   - Fenghua Liu, M.S. candidate

10. **Radial Acceletron**
    (AFOSR/MURI/AASERT/AFRL)
    - Prof. Edl Schamiloglu
    - Robert Wright, Ph.D. candidate
    - Drs. Mo Arman, John Luginsland, Kyle Hendricks, Tom Spencer, Diana Loree, and Sgt. Walt Fayne (all AFRL/Phillips)

11. **Educational Reltron HPM Source**
    (AFOSR/MURI/DURIP'96)
    - Prof. Edl Schamiloglu
    - Dr. R.B. Miller (consultant to Titan/PSI)

12. **HPM Characterization of Photonic Crystals**
    (AFOSR/MURI and ARO joint effort)
    - Prof. Edl Schamiloglu and Prof. Kevin Malloy
    - Dr. Frank Hegeler
    - Dr. Kamil Agi, Research Associate
    - Mohammad Mojahedie, Ph.D. candidate

13. **Smith-Purcell Free Electron Laser**
    - Prof. Edl Schamiloglu and Prof. S.R.J. Brueck (UNM CHTM)
    - Dr. Frank Hegeler (UNM)
    - Prof. Neville C. Luhmann, Jr. and Prof. Jonathan Heritage (UC-Davis)
    - Dr. Fred Hartemann (UC-Davis)

PERSONNEL AT UNIVERSITY OF MICHIGAN
R.M. Gilgenbach (Project Director)
Y.Y. Lau (Co-Principal Investigator)

<u>Task</u>

14. **Microwave Pulse Shortening Mechanisms and Mitigation, Coaxial Gyroton**
    - Prof. R.M. Gilgenbach (directs experimental research)
    - Prof. Y.Y. Lau (directs theoretical research)
    - R. Jaynes, graduate student (coaxial gyrotron oscillator)
    - W. Cohen, graduate student (plasma cleaning of high power microwave gyrotron and collaboration with SLAC on plasma processing of high power microwave components)
    - C. Peters, graduate student (time-frequency analysis)

15. **Theoretical Work on Microwave Multipactor on Windows and Microwave Beam Loading**
    - Prof. Y.Y. Lau (directs research)
    - A. Valfells (graduate student)
    - L.K. Ang (graduate student)

16. **Thermionic Cathodes**
    - Professor (Emeritus) Ward Getty (now retired)
    - D. Vollers (USAF) (graduate student)
    - M. Johnston, (summer student)

PERSONNEL AT MICROWAVE SCIENCES, INC. (MSI)
Dr. Jim Benford, Principal Investigator

Task

17. **Pulse Shortening in HPM Generators**

18. **Transition to Better HPM Source Surface and Vacuum Conditions**

19. **Low-Closure-Rate Cathode Materials at High Electric Fields.**

20. **Vircator Studies**

EXECUTIVE SUMMARY

The AFOSR MURI Central Consortium was composed of faculty members and students from Texas Tech University (Coordinating University), The University of New Mexico, and The University of Michigan with collaboration from Microwave Sciences, Inc. The participants came from Electrical Engineering, Physics, Materials Science, Computational Systems, and Nuclear Engineering. The research at each university complemented that at the other universities and covered Vircators, High Efficiency Backward Wave Oscillators, Fast Wave Gyro Devices, Plasma Filled Devices, Ferroelectric Cathodes, Ultra Wideband Technology, Microwave Vacuum and Window Breakdown, Multipactor Phenomena, "Smart" Tube Technology, Advanced Cathodes, Radial Acceletrons, Transit Time Oscillators, and Free Electron Lasers. The overall emphasis of the proposed research was to increase the device efficiencies and to reduce their weight and volume. Efforts to increase the radiofrequency vacuum strength of cavities and windows hold promise for higher energy density devices. Novel cathodes may lead to longer pulse devices resulting in higher energy sources. An important aspect of the program was to research various control strategies relevant to pulsed high power microwave sources. An assessment of expert systems and its usefulness to these sources was made. Active collaboration has taken place with industrial companies, especially Primex Physics International Co. and Titan, as well as Sandia National Laboratories. The historically close cooperation between the three universities and the Air Force Research Laboratory (Phillips Site) was expanded and strengthened. The USAF is the lead agency in this field and the largest DoD effort is at the Air Force Research Laboratory at Kirtland AFB in Albuquerque, NM. Because of this, as well as geographical considerations and historical ties, the Central Consortium has had particularly strong ties to the Phillips Site.

Texas Tech University (TTU) emphasized the High Power Microwave (HPM) window breakdown work using the exceptionally well diagnosed traveling wave resonant ring facility. The ring was obtained from SLAC and DURIP funds were used to upgrade the diagnostics. Collaboration with the Univ. of Michigan group produced new results on multipactor theory. Window materials were tested for Sandia National Laboratory and MDS, Inc. It was shown that window breakdown due to HPM at frequencies below about 35 GHz exhibits the same physics as unipolar pulse flashover on a dielectric in vacuum. A simple model describing HPM window breakdown was developed. Dielectric-gas interface breakdown was investigated and shown to depend somewhat on the gas and, also on the risetime of the microwave power.

The study of subnanosecond breakdown phenomena in gases and liquids was implemented with high-speed digitizers and a streak camera. Fields as high as 12 MV/cm were achieved at high pressure in gases and the breakdown delay decreased to 0.8 ns, while in oil the delay was as short as 0.6 ns. Comparison with previously published work indicated that extrapolation of those data to shorter times was not physical. One surprising result was that the old trick of illuminating the cathode with UV light to collapse the statistical scatter of breakdown delays did not work at high pressures. Due to information from researchers at AFRL, Phillips Site, the effort was changed to investigate the production of corona by short pulses. Corona due to very short length, short risetime pulses was detected after a sufficient number of pulses.

A vircator with coaxial geometry was tested after promising results obtained under another research contract. Computer modeling combined with experiments produced an efficiency increase of a factor of 15. A further increase in efficiency was obtained by use of a reflector, which raised the microwave power retained in the vircator cavity. To investigate pulse shortening, the pulse applied to the vircator was increased in length, but results are not available yet.

A theoretical study of the effects of plasma filling was conducted using the parameters of the high power BWO at UNM. The MAGIC code was used to simulate the electron density distribution and the microwave power generated by the electron beam in the presence of a background plasma. The results were that plasma filling should produce a stable beam and an increase in efficiency.

A proof of principle investigation of a modulating scheme for an extreme relativistic electron beam to produce 10 GHz microwaves was started. The numerical simulation showed that a relativistic beam (1 MeV) can be bunched and produce microwaves with an efficiency of about 55%. The experimental phase was designed to demonstrate this principle with a 100 keV, 10 mA beam which would have been sufficient. Experimental difficulties in the experimental demonstration led to termination of the project without positive results.

An attempt to build a 94 GHz, 4-cell Klystron cavity was successful in that cavities with the required dimensions were constructed. However, none of the cavities were of high enough quality to justify application of an electron beam to test microwave generation.

The University of New Mexico (UNM) demonstrated tunability of a vacuum BWO and an efficiency of 25%. The understanding of applicability of PIC codes and the use of experimental data as input was expanded. A cathode mounted plasma source was designed and used to demonstrate a 35% increase in efficiency for a long pulse BWO. UNM and TTU collaborated on the plasma theory.

The study of ferroelectric cathodes showed that they act as plasma emitters under high fields. This led to the development of a thin film ferroelectric, which emits electrons at very low applied voltages which could be of use in flat panel displays.

Collaboration with Russian scientists produced a mode converter that was used to study EM wave propagation and showed that it could be used with the gigawatt "smart" HPM source.

The soon to be printed book "Advances in High Power Microwave Sources and Technologies" was co-edited by Professor Schamiloglu at UNM.

The University of Michigan (UM) has pursued a number of experimental investigations aimed at developing an understanding of the mechanisms for high power microwave generation and of

the effects causing pulse shortening. The facility used was the Michigan Electron Long Beam Accelerator (MELBA).

Gyrotron cavities were tested with and without a coaxial rod, and with and without slots. The coaxial rod seems to raise the limiting electron beam current and, therefore, the output power. Time-frequency analysis (TFA) was used to show that pulse shortening was caused by e-beam voltage fluctuations, mode competition, and mode hopping. These could be controlled by magnetic tuning.

Temporally resolved optical spectroscopy showed that the appearance of a hydrogen plasma coincided with the decay of the microwave power. Plasma cleaning using a 13.56 MHz, 50-watt generator with a low pressure of nitrogen gas produced a significant increase (up to 245%) in pulse length and energy.

Experiments with a rectangular cross-section (RCS) gyrotron demonstrated switching between the two orthogonal polarizations by changing only the magnetic field. An active-circulator gyrotron traveling wave amplifier should be possible using the results from the RCS.

Theoretical investigations included a revolutionary new look at multipactor phenomena on both metals and dielectrics. The application of TFA to the HPM generator opened up a new way to analyze mode hopping, mode competition, and plasma production.

Collaboration with AFRL, Phillips Site scientists produced theoretical and simulation results of great value for understanding the Injection-locked Relativistic Klystron Amplifier, the Relativistic Klystron Oscillator, and the Magnetically Insulated Line Oscillator.

Microwave Sciences, Inc. (MSI) concentrated on understanding the physics of, and overcoming the problem of, pulse shortening. Observations of, and theories of, pulse shortening were reviewed and a general model was developed. The cause of pulse shortening in the relativistic magnetron was identified.

Work on new cathode materials included demonstration of the CsI cathode for a HPM generator at Pulse Sciences, the oxide cathode work at UNM, and the new carbon-carbon fiber material in use at AFRL, Phillips Site.

Valuable consultation on the coaxial vircator at TTU helped produce a higher efficiency and the promise that feedback into the vircator cavity could raise the efficiency considerably.

BRIEF SUMMARY OF ACHIEVED CONTRACT GOALS

Texas Tech University

In this section we are addressing those research topics that were proposed in the original MURI grant proposal.

MICROWAVE VACUUM AND WINDOW BREAKDOWN

The work on window breakdown due to high power microwaves got an early start because a Traveling Wave Resonant Ring (TWRR) was obtained from the Stanford Linear Accelerator Center (SLAC). Operating at 2.86 MHz, the TWRR produced 80 MW of traveling wave from a 3 MW magnetron. The TWRR was modified to allow insertion of dielectric slabs in the waveguide. Diagnostics were added to the TWRR to measure the microwave electric field upstream and downstream of the dielectric sample, visible light generated on the sample, x-rays generated at and in the vicinity of the sample, and also allowing for fast, gated CCD images and time-resolved spectroscopy of the light emitted from the breakdown event on the sample.

The first measurements for microwave power incident, in vacuum, on a standard SLAC alumina window showed that the diagnostics could correlate the events leading to breakdown on the surface on a nanosecond scale. Next, measurements on polymer insulators, such as Lucite and Lexan, showed that the surface breakdown exhibited the same characteristics as surface breakdown in vacuum using relatively slowly rising (μs) unipolar pulses. A simple calculation shows that this should be the case for microwave frequencies up to about 35 GHz, at which point the electrons in the surface avalanche can no longer follow the electric field. The breakdown event was characterized by correlating the data from the electric field probes, the optical emission, and the x-ray emission. Before breakdown, the upstream and downstream electric fields show the same field intensity, there is no optical signal, and the x-ray emission rises slowly as the secondary electron avalanche on the dielectric surface grows. When breakdown occurs, the downstream electric field drops and the upstream field increases due to reflection of the microwave power by the plasma. Optical emission increases as the surface plasma develops on the dielectric, and the x-ray emission ceases as soon as the gas density is high enough to limit the mean free path of the electrons. After that the microwave power falls because the Q of the TWRR is lowered.

A simple model describing vacuum-dielectric-vacuum breakdown due to high power microwave power has been developed. This model incorporates a spatially varying electron density in the direction normal to the dielectric surface. By comparing modeled parameters with the experimental results we can identify the physical mechanisms responsible for the breakdown initiation.

The microwave magnetic field can exert significant force on the secondary electrons if the electron velocity is high and the field is large. We observed such effects in experiments on dielectric slabs. The electrons on the downstream side were driven away from the surface, thus raising the power level at which a plasma would develop on that side. These measurements

required one side to be coated with a material which increases the breakdown field so that observations could be restricted to the side of interest. We used a coating developed in our labs which we call "Pixie Dust". This coating might actually be of technical interest, but it only works in vacuum and one breakdown event will remove it from the surface.

Dielectric-gas interface breakdown was measured for a variety of gases. The travelling wave resonant ring (TWRR) was modified to produce a pressurized test region capable of pressures up to 10^3 Torr. Dielectric surface breakdown strengths were then studied from 10^3 Torr down to 10^{-4} Torr for air, SF_6, and argon, and compared to our previous results for breakdown in vacuum. Additionally, volume gas breakdown was studied within the test region and compared to the dielectric interface breakdown strengths. Finally, a literature search produced data for comparison to the acquired results. At high pressures, 0.1 Torr to 10^3 Torr, dielectric-gas surface breakdown fields and volume breakdown fields as a function of pressure displayed a similar relation, with slightly lower breakdown fields for dielectric-gas interfaces due to the field enhancement caused by the dielectric. Drastic differences appear when comparing volume and dielectric breakdown at lower pressures, because then free electrons play a dominant role, as exhibited by a significant increase in the x-ray signal. Dielectric-gas breakdown field strengths for air, SF_6, and argon are similar at low pressures, but diverge at high pressures. This is consistent with free electrons dominating breakdown at low pressures, while gas ionization processes dominate at high pressures. SF_6 exhibited the highest breakdown field strength at high pressure (atmosphere) and argon exhibited the lowest. The volume breakdown results were compared to results from the literature and showed a similar trend for breakdown field strengths as a function of pressure. Absolute breakdown levels were not comparable except in one case. This difference was associated with the short rise- time, linearly rising field in our TWRR compared to the constant field over a long time associated with the data in the literature. Our data represents the lower limit of breakdown fields on alumina interfaces and can be used as a guideline for window design. These results have been presented at SPIE Aerosense 2000 in Orlando, FL, and will be presented at ICOPS 2000 in New Orleans, LA, and BEAMS 2000 in Nagaoka, JP.

Brief summary of related scientific achievements:

- At 2.86 GHz, μwave initiated surface breakdown on a dielectric in vacuum is caused by the same physical mechanisms that apply to dc breakdown.
- The microwave magnetic field plays an important role in dielectric surface breakdown in vacuum causing a difference in breakdown field of up to 25% between the upstream and downstream surfaces.
- Correlated measurements with high-speed sensors in a TWRR can produce a detailed understanding of dielectric surface breakdown in vacuum and in gas.

ULTRAWIDE MICROWAVE GENERATION

This task began under the title "Sub-nanosecond Breakdown Phenomena". The breakdown of gases and liquids was investigated using ultra fast diagnostics and high voltage pulsers producing 100's of kV with risetimes in the 0.2 to 1.0 ns range. The test chamber incorporates capacitive E-field sensors on either side of the electrode gap which are connected to Tektronix SCD-5000 transient digitizers with a risetime of 80 ps. The progress of the breakdown plasma in the gap was recorded with a streak camera for both liquids and gases.

The gases investigated include air, N_2, H_2, He, and SF_6. Liquids include transformer oil and Freon-12. The test chamber is constructed to support pressures up to 2000 psi. The generator used originally was a 250 kV, 1 ns risetime unit. A pulser with a risetime of 0.5 ns and an amplitude of 700 kV was built and used to obtain most of the results. The large amplitude is necessary so that the electrode gap can be increased to a reasonable value and avoid effects due to surface imperfections on the electrodes.

Data was obtained for the gases over a pressure range from atmospheric to 1200 psi. For example, air at 15 psi and 0.4 MV/cm exhibited a breakdown time of 1.3 ns. At 750 psi and 2.75 MV/cm, it was 0.65 ns. For SF_6, at 15 psi and 0.55 MV/cm, the delay was 1.3 ns, but at 115 MV/cm and 2.8 MV/cm, it was 0.8 ns.

Transformer oil was filtered before tests to remove particulate matter which is know to lower the breakdown strength. At 6MV/cm, the oil breakdown delay was 1.2 ns. The field was raised to 12 MV/cm by decreasing the gap spacing, and the delay time dropped to 0.6 ns.

For breakdown in gases, the data were compared with the results of previous experiments and with a model based on gas density. Neither of these were carried to the short times described here so the E-field versus delay time from those references were extrapolated into the subnanosecond regime. Data from this experiment agreed with both earlier works at long times, but showed a steeper slope at shorter times. In other words, a higher field is required to obtain the same delay time. For H_2 gas, this amounts to a factor of about 8 at 300 psi.

When the cathode was illuminated with UV light, the statistical scatter in the breakdown voltage was drastically reduced at low gas pressure as expected from previous work. However, at high pressure, 17 atm., the UV had no measurable effect.

Interaction with the UWB experimenters at AFRL, Phillips Site, indicated that an important problem with radiating UWB power might be the formation of a corona discharge at the antenna after some number of pulses. The equipment used to measure breakdown time in gases was modified to produce corona due to ns length, rep-rated pulses. The coaxial chamber consisted of a 0.3 mm dia. stainless steel wire as the center

conductor with a copper mesh outer conductor inside a pyrex cross, so that optical emission could be detected. This produced a coax line with impedance of 290 ohms. The pulse generator was a 200 ps risetime, 700ps pulse length, 10kV pulse amplitude, solid state unit with a rep-rate variable from 0.1 to 6 kHz. The E-field sensors and transient digitizer were as for the gas breakdown work. The luminosity from the corona discharge was detected with an 800 ps risetime photomultiplier. When a corona discharge occurred, the power transmitted through the coaxial corona chamber dropped due to the change in impedance. For example, the transmitted power dropped by 25% as the rep-rate was increased from 53 Hz to 3 kHz. Unfortunately, no pulser was available with a voltage higher than 10kV and the required rep-rate, so all of the results are for pressures below atmospheric, down to 10 Torr. However, the results should scale as E/p and should, therefore, serve as a guide for UWB work.

Brief summary of related scientific achievements

- The breakdown delay time in gases (air, H_2, He, N_2, SF_6) was measured for high E-field (up to 3MV/cm) and found to be longer than expected from previous work.

- The breakdown delay time in transformer oil was shown to be approximately linear with E-field.

- A corona discharge will form in air subjected to a high E-field pulse after a number of pulses even if the pulse is of sub-nanosecond duration.

ALTERNATE VIRCATOR GEOMETRIES

The work on alternate vircator geometries began with comparison tests of a planar vircator with a simple coaxial vircator. This was a result of a Ph.D. student's dissertation work and appeared promising. Analytical and experimental tests were conducted under an AFOSR contract and then under MURI. The continued research under MURI funding comprised most of another student's Ph.D. dissertation work.

Vircators are simple devices to construct and operate with little fine adjustments but suffer from low efficiencies, typically around 1%. Russians have claimed efficiencies above 10% with alternate geometries, but this claim was met with skepticism. The main goal is to develop and test alternate geometries that provide enhanced efficiencies.

Initial tests were performed with MAGIC and SOS, 2.5 and 3 dimensional, fully relativistic particle-in-cell codes. These simulations were analyzed and the geometries were built and tested. The simulations most promising results showed that a negative polarity geometry would double the efficiency. Experimentation with this geometry showed approximately a doubling of the efficiency over the positively pulsed geometry. Another significant achievement was the discovery that narrow emitters produce higher efficiencies. The use of narrow emitters and a negative geometry resulted in an increased efficiency 15 times that of the original

positively pulsed coaxial vircator. The typical electron-beam parameters included a 50 kV, 40 kA, 30 ns pulse with output microwave powers of 400 MW at 2 GHz.

The efficiency was expected to be further improved by increasing the microwave field strength around the vircator. The microwave field intensity around the virtual cathode oscillator was enhanced by using a microwave reflector in the output waveguide. The experimental results show that the microwave output power strongly depends on the position and geometry of the microwave reflector. The maximum microwave energy efficiency obtained was more than twice as large (~ 5.5%) as that without field enhancement by the microwave reflector and the output microwave power increased to nearly 1 GW. This work was terminated on July 31, 1999 but has been revived with other funding. The new work is to increase the pulse length. Since the microwave power was still rising when the input pulse shuts off, it is believed that the maximum output power has still not been reached and therefore the maximum efficiency has not been achieved.

Brief summary of related scientific achievements

- Negative polarity geometry improved the efficiency of the original positively pulsed coaxial vircator geometry by about a factor of two.
- Narrow emitters provide an increase in efficiency over the original positively pulsed coaxial vircator geometry. When used in conjunction with a negative polarity geometry provided an increase in efficiency of about 15 times.
- The use of a microwave reflector strengthened the microwave field intensity around the virtual cathode which more than doubled the efficiency of the geometry without the reflector.

THEORETICAL MODELING OF INTERACTIONS IN PLASMA FILLED MICROWAVE GENERATORS

A theoretical and computational study of the backward wave oscillator of UNM configuration was performed to understand the interactions between electron beam, microwave, and plasmas. The particle simulation by the MAGIC code revealed some features of microwave power generation in the presence of background plasma. The results were reported in subsection 7.3 of Chapter 7 of the Advances in High Power Microwave Sources and Technologies (ed. by Barker and Schamiloglu, IEEE Press, 2001).

DEFLECTING EXTENDED INTERACTION KLYSTRON AND 94 GHz 4-CELL KLYSTRON CAVITY

A proof of principle investigation of a deflecting extended interaction klystron was the objective of this activity. In the scheme, microwave power at 10 GHz is generated by conversion of kinetic energy of a relativistic electron beam. Periodic deflection of the electron beam is used to yield time-of-flight bunching due to modulation of the length of the trajectory rather than

modulation of the speed of the electrons. This bunching scheme can be applied to extreme relativistic electrons. The numerical simulation predicted a conversion efficiency for a finite-emittance beam at an electron energy of 1 MeV of about 55%. For budgetary reasons the design value for an experimental investigation was reduced to 100 keV electron energy. The theory of the deflection of the electron beam in the cavity and the growth rate of the oscillation at turn-on has been investigated further. In the reduced proof of principle experiment a minimum electron current of about 10 mA through the cavity was needed at a beam potential of 70 keV. With these parameters the field would have been established in the cavity in less than 0.5 μs.

Several multi-cell cavities were built. The field distribution on axis was measured using a perturbation technique. In addition a single-cell deflecting/decelerating resonator was machined with a resonant frequency of 10.2 GHz.

An experimental set up was built using extraction of an electron current from a plasma source. The beam current showed large fluctuations and was not sufficiently reproducible. As the extraction region got more contaminated, the breakdown of the extraction gap occurred earlier, shortening the electron pulse to about 2 μs. The primary contamination is assumed to have come from the plasma source.

To gain better reproducibility the plasma cathode was replaced by an old, nearly burned out thermionic emitter. An electron beam of 20 mA was extracted from this cathode in a preliminary extraction configuration at a heating current of 1.8A, which was significantly higher than allowed by the manufacturer's specifications and finally caused burn-out of the filament. A new cathode was acquired and the system was modified with existing vacuum components (DURIP) to achieve a better vacuum in the cathode region. The new vacuum system achieved a base pressure of 5×10^{-8} Torr with the deflecting magnet in place and the cathode turned off.

Also the extraction was changed to a pulsed mode. A pulsed extraction circuit was built and yielded a 20 μsec extraction pulse of about 4 kV. Severe financial and personnel limitations dictated in 1998 the need to perform the proof of principle experiment with a bare bones setup, which incorporated the single deflecting-decelerating crossed-beam cavity. After the cathode was activated an electron current of less than 0.5 mA was extracted while the filament current was kept within the range specified by the manufacturer. Observation of the color of the cathode through a window indicated that the cathode did not heat to the required temperature with the specified heater current.

At the end of August 1998 the financial support and the investigation were terminated, due to the consolidation of the financial and personnel resources.

The objective of the 94 GHz 4-cell Klystron cavity project was to show that a multi-cell cavity resonator for 94 GHz could be built using mechanical and chemical machining, and electroplating. Several 4-cell klystron cavities for a frequency of 94 GHz were built. They have an inner diameter of 2.55 mm and a period of 0.66 mm. The cell membranes (irises) have a thickness of 0.2 mm and an aperture of 0.79 mm diameter. A low-melting point silver solder was used for brazing. Inspection of a cut open cavity under the microscope showed flaws in the brazing and the copper plating. Drilling coupling holes of 0.4 mm diameter into the cavity was not always successful due to the shape of the available drills and the softness of the copper. These

problems would have to be addressed in the future. It was shown that the suggested manufacturing process allows the construction of multi-cell cavities at 94 GHz. At the end of August 1998, the financial support and investigation were terminated.

University of New Mexico

In this section UNM is addressing those research topics that were proposed in the original MURI grant proposal:

1. **HIGH EFFICIENCY VACUUM BWO'S USING UNIFORM AND UNIFORM SLOW WAVE STRUCTURES ACHIEVEMENTS:**
Demonstrated novel tunability of high power BWO's using phase difference between backward and forward propagating harmonics. Demonstrated 25% beam-to-microwave power conversion efficiencies. Expanded understanding of PIC codes and demonstrated that experiments can be used to baseline certain inputs into PIC codes (numerical damping coefficients in particular). Transitioned this understanding to long pulse BWO's.

2. **PLASMA-FILLED, LONG PULSE BWO'S ACHIEVEMENTS:**
Designed novel cathode-mounted plasma prefill source. This allows plasma to be injected downstream from the cathode prior to electron beam injection, and this then allow flexibility in mode extraction since no plasma hardware is located at the output end of the system. Demonstrated 35% increase in efficiency of long pulse (< 100 ns) microwave generation with plasma compared to the vacuum case. Observed no frequency shift due to plasma. This is because of the density regime in which we operated.

3. **FERROELECTRIC CATHODES FOR HIGH POWER MICROWAVE TUBES ACHIEVEMENTS:**
Demonstrated that ferroelectric cathodes operate as plasma emitters when used on intense beam sources operating at 100's kV at 1-cm scale A-K gaps. Shifted focus to study thin film ferroelectrics that could be of interest to flat panel displays. Developed a novel thin film ferroelectric cathode stoichiometry that demonstrated reliable, reproducible electron emission (very low current densities) at 1-volt scale voltages.

4. **HIGH POWER ELECTROMAGNETICS: MODE CONVERTORS ACHIEVEMENTS:**
Designed and built a serpentine TM_{01} to TE_{11} mode convertor (in collaboration with Institute of Applied Physics in Nizhny Novgorod, Russia). Demonstrated that a mode convertor can be made a critical component of a Smart Tube HPM source. Used this Smart Tube to study fundamental aspects of electromagnetic wave propagation in regions of anomalous dispersion.

5. **CONTROL OF HIGH POWER MICROWAVE TUBES ACHIEVEMENTS:**
Invented Gigawatt-Level Smart Tube HPM Source

BRIEF SUMMARY OF RELATED SCIENTIFIC ACCOMPLISHMENTS

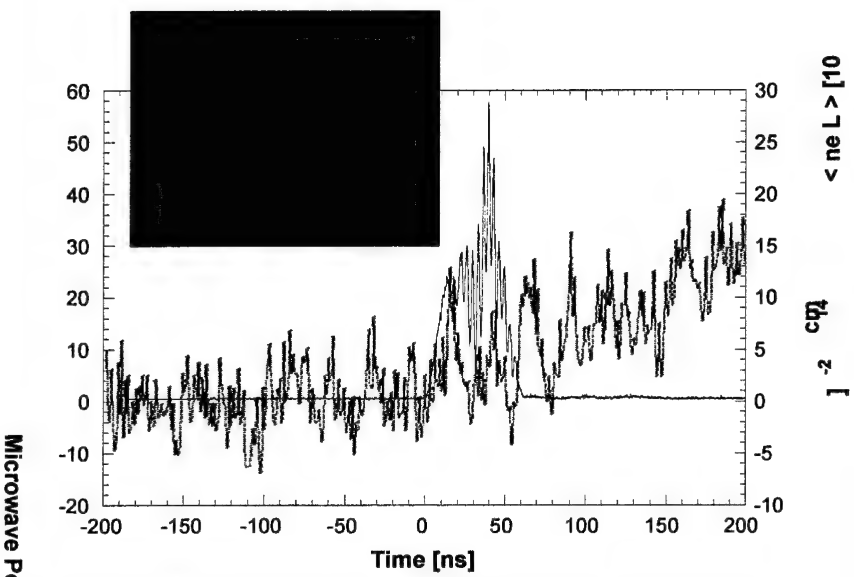
- Book entitled Advances in High Power Microwave Sources and Technologies is to be published by IEEE Press, Professor Edl Schamiloglu (UNM, co-editor) and Dr. Robert J. Barker (AFOSR, co-editor.

- See following viewgraphs

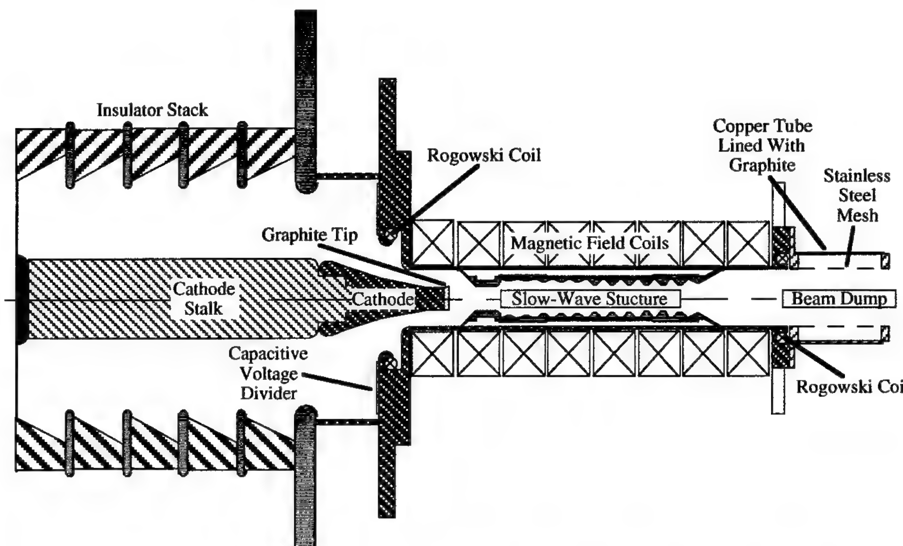
HPM MURI Accomplishment: Pulse Shortening in HPM Sources

University of New Mexico
Department of Electrical and Computer Engineering
Pulsed Power and Plasma Science Laboratory

- Investigation of plasma emission using various SWS wall coatings (microwave pulse duration increased by 50% from 100 ns to 150 ns).
- Correlation between microwave pulse shortening and plasma emission (first direct measurements of plasma in an HPM source during microwave generation).
- Assessment of modifications to mitigate pulse shortening.
- Implementation of the Hybrid Hard Tube BWO (Titan/PSI).
- Use of Bragg reflector to replace cutoff neck in BWO (collaboration with the Institute of High Current Electronics, Tomsk).



Line-integrated plasma density during HPM generation.



Experimental setup of the long pulse BWO.

HPM MURI Accomplishment:
GW Level Smart Tube HPM Source

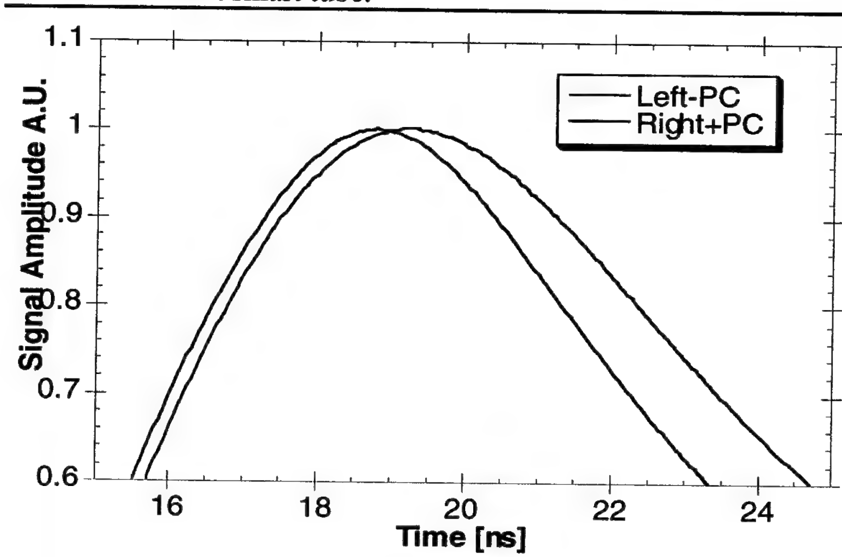
University of New Mexico
Department of Electrical and Computer Engineering
Pulsed Power and Plasma Science Laboratory

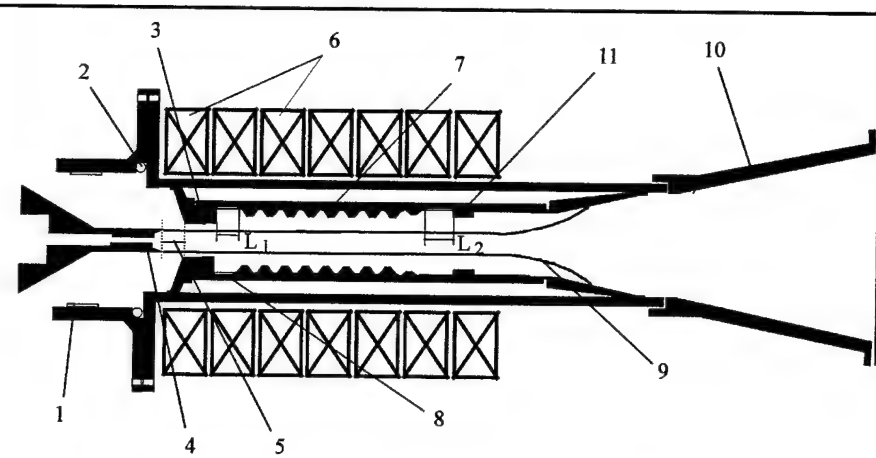
Computer-controlled vacuum phase shifter – the essence of the GW level HPM smart tube.

- Demonstrated reliable operation of computer-controlled Smart Tube, frequency-agile HPM source.
- First time-domain measurement of electromagnetic "tunneling" through the stop band of a 1-D photonic crystal.

Red: EM wave propagating in free space.

Blue: EM wave "tunneling" through 1D photonic crystal (superluminal group velocity).

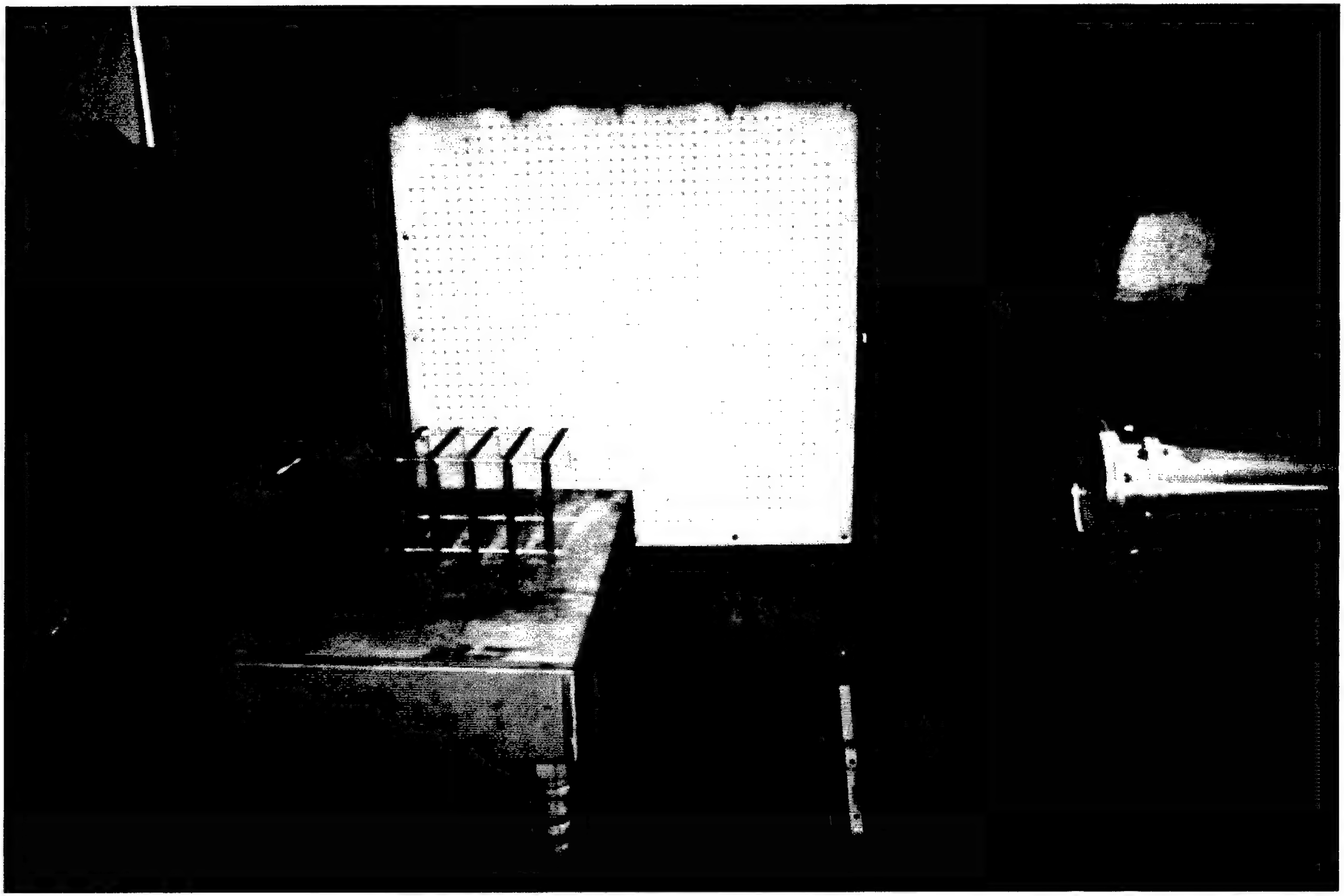




Experimental setup for BWO experiments with forward and backward shifting (axial displacement of the slow wave structure). Shown in the diagram are (1) capacitive voltage divider, (2) Rogowski coil, (3) cutoff neck, (4) cathode, (5) A-K gap, (6) magnetic field coils, (7) slow wave structure, (8) smooth circular waveguide and shifting lengths L_1 and L_2, (9) electron beam, (10) output horn antenna, and (11) reflection ring (not used).

HPM MURI Accomplishment: Superluminal EM Wave Propagation Through Stop Band of 1D Photonic Crystals

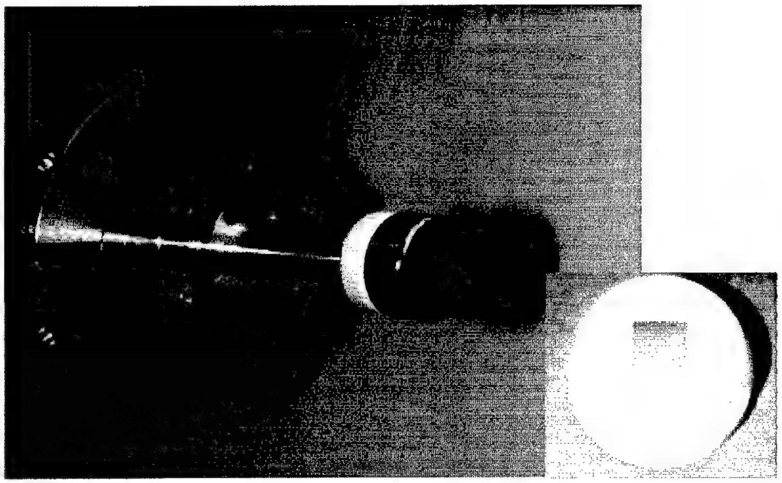
University of New Mexico
Department of Electrical and Computer Engineering
Pulsed Power and Plasma Science Laboratory



First time-domain measurement of electromagnetic "tunneling" through the stop band of a 1-D photonic crystal.

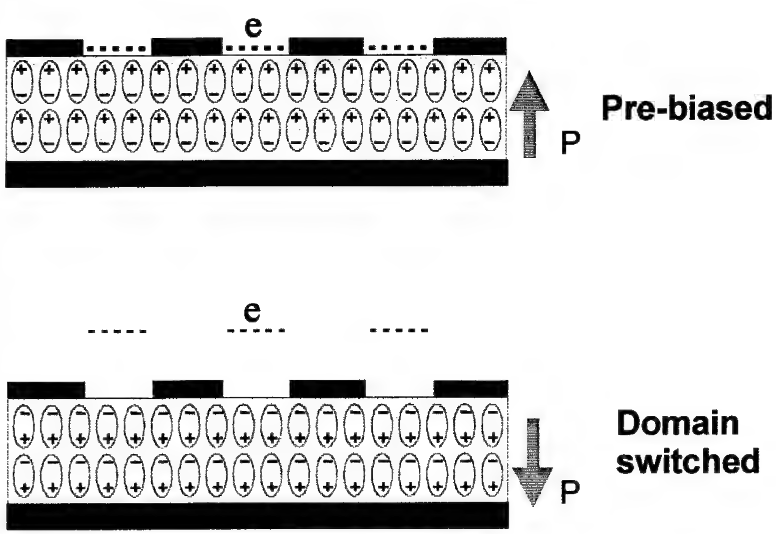
HPM MURI Accomplishment:
Thin Film Ferroelectric Cathode

University of New Mexico
Department of Electrical and Computer Engineering
Pulsed Power and Plasma Science Laboratory

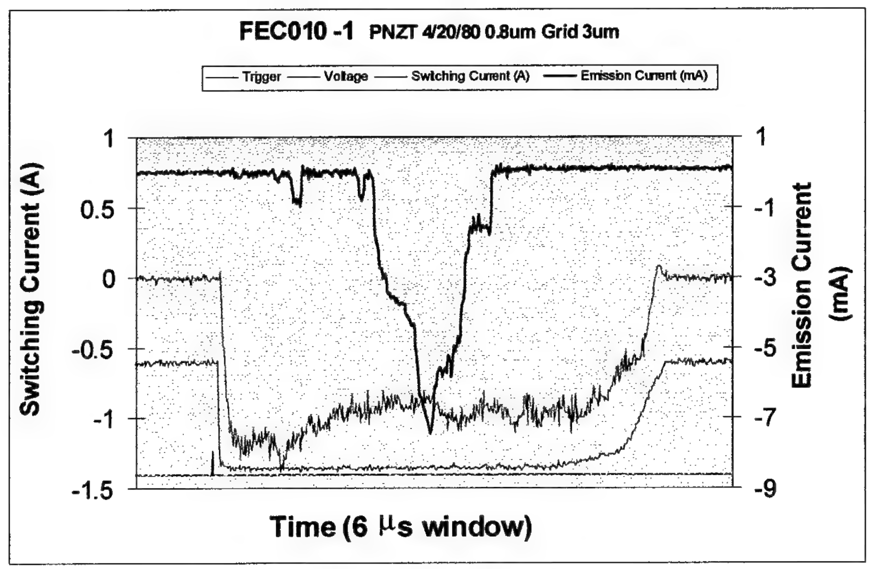


Experimental setup with ferroelectric cathode (1 cm x 1 cm).

- Systematically investigated thin film ferroelectric cathodes.
- Applied semiconductor processing methods to grow thin films.
- Matching cathode thickness to top electrode spacing (about 1μm).
- Potential application: Flat Panel Displays.

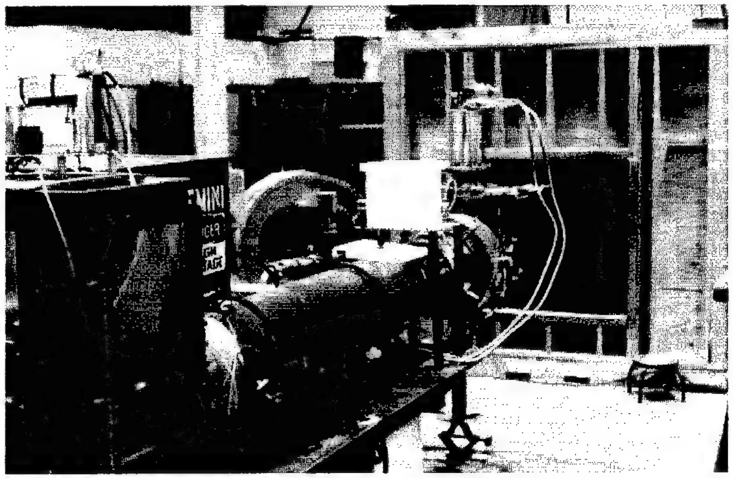


Ferroelectric electron emission mechanism.



HPM MURI Accomplishment:
Radial Acceletron HPM Source at AFRL

University of New Mexico
Department of Electrical and Computer Engineering
Pulsed Power and Plasma Science Laboratory



Gemini Pulser and Radial Acceletron at the AFRL (Phillips Site).

- MURI/AASERT-Funded collaboration between UNM and AFRL/Phillips Site. Work performed on-site at AFRL led by UNM Ph.D. candidate in collaboration with AFRL staff.
- HPM source designed electronically. Experiments and modified simulations led to success.

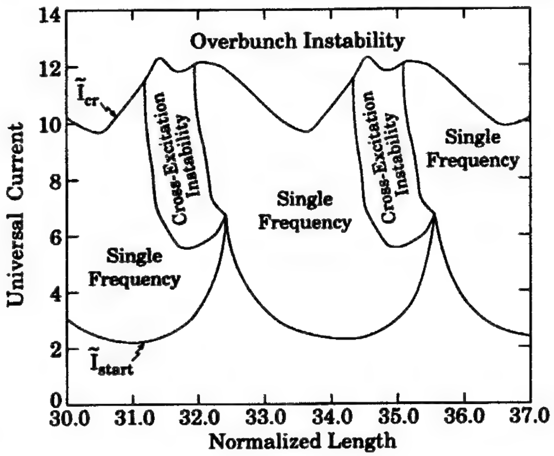
- Microwaves generated, consistent with predictions of MAGIC particle-in-cell simulations.
- Output is sensitive to Q of the cavity, consistent with analytical models.

- The Gemini Pulser Blumlein was extended to increase pulselength to about 300 ns.
- Optimization of rf output underway.
- Ph.D. to be completed by end of summer 2000.

University of New Mexico
Department of Electrical and Computer Engineering
Pulsed Power and Plasma Science Laboratory

HPM MURI Accomplishment: First Observation of BWO Instability

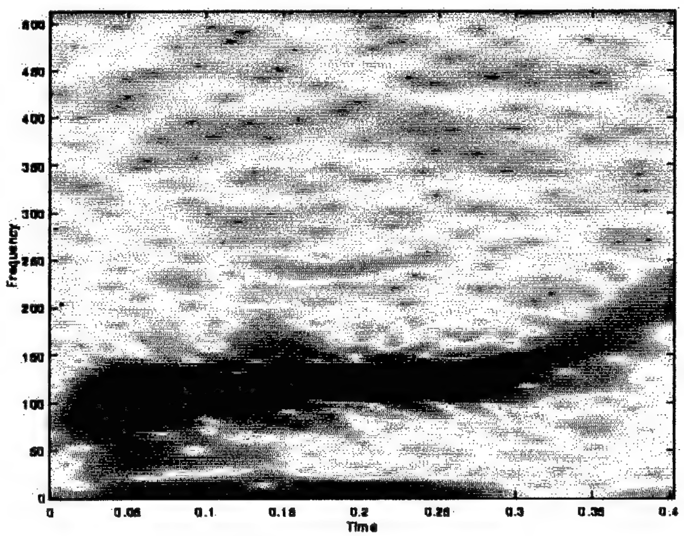
Levush *et al.*: IEEE Transactions on Plasma Science, June 1992, pp. 263-280.



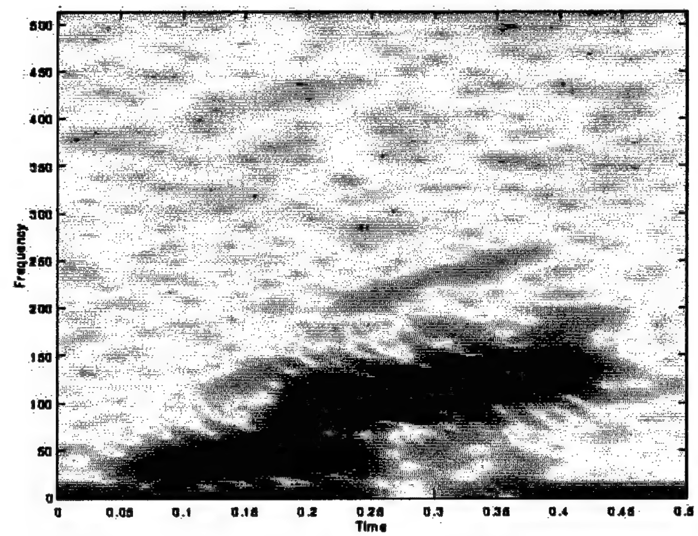
Regions of BWO operation. The reflection coefficient is 0.7.

Cross-Excitation Instability

- First experimental observed of the cross-excitation instability in relativistic BWO in vacuum. Confirms predictions of Levush *et al.* (University of Maryland) theoretical model.
- Possible application to rf effects studies.



JTFA corresponding to the single frequency regime.



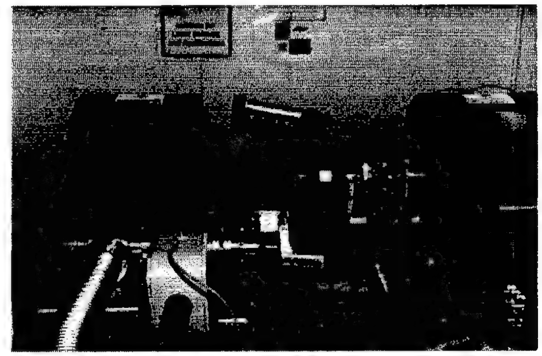
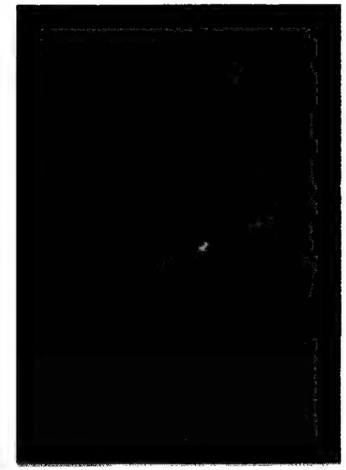
JTFA corresponding to the cross-excitation regime.

HPM MURI Accomplishment: UNM and UC-Davis Team Up

University of New Mexico
Department of Electrical and Computer Engineering
Pulsed Power and Plasma Science Laboratory

A Smith-Purcell Free Electron Laser Based on the UC-Davis X-Band Photoinjector

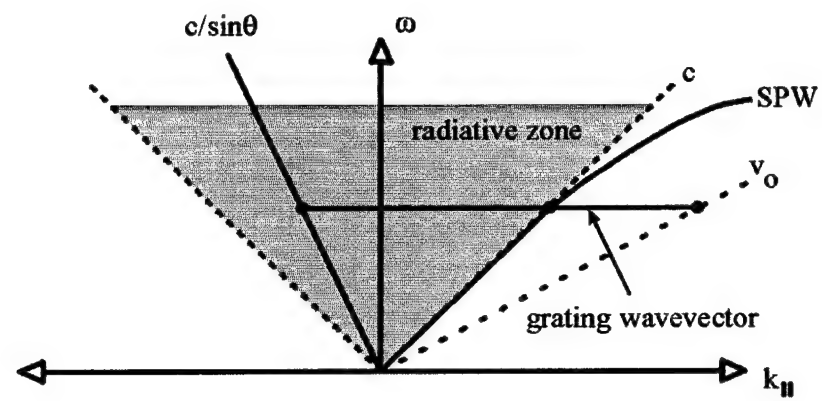
A collaboration between
The University of New Mexico, UC-Davis, and The Institute for Laser Science and Applications (ILSA).

X-band photoinjector at the ILSA.

Edl Schamiloglu,* S.R.J. Brueck,* Frank Hegeler,* Fred V. Hartemann,** Neville C. Luhmann, Jr.,** and Jonathan P. Heritage.**

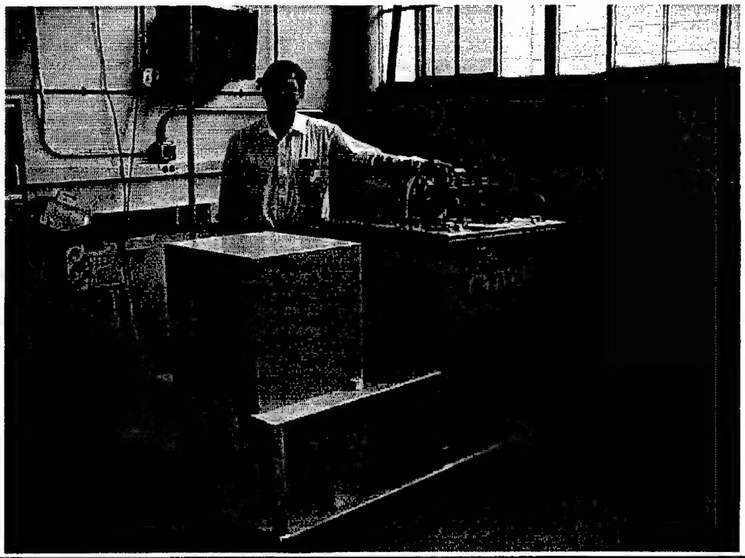
* University of New Mexico
** University of California at Davis



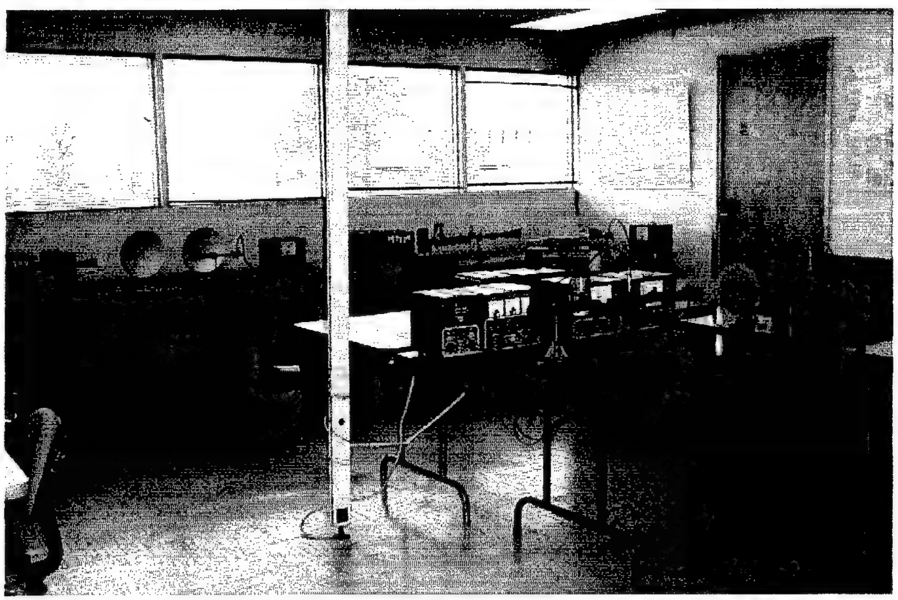
Second-order backward wave coupling suggested by UNM.

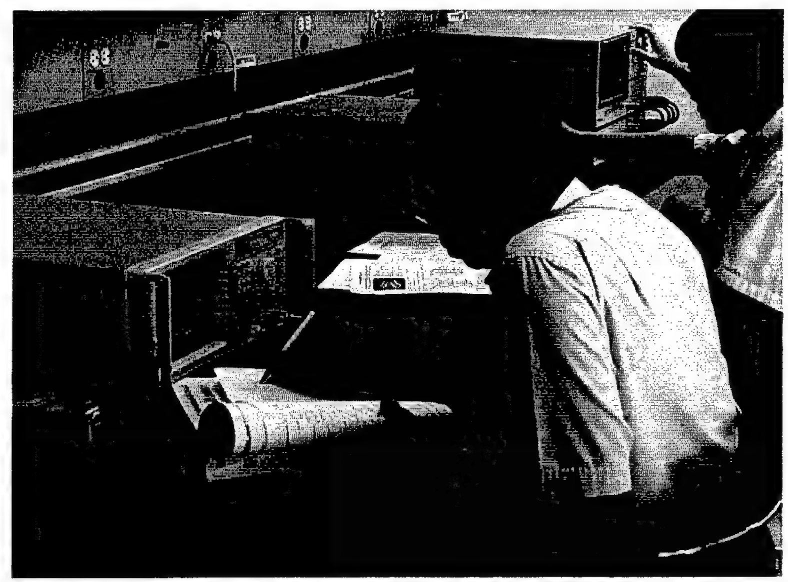
HPM MURI Accomplishment: DURIP-Funded μWave Education

University of New Mexico
Department of Electrical and Computer Engineering
Pulsed Power and Plasma Science Laboratory



- Compact Reltron (100 kV, 2 μs, 10 MW @ 3 GHz) for graduate student education in HPM *(see left picture)*.
- New introductory undergraduate/graduate microwave laboratory with X-band microwave workstations and network analyzers *(see bottom pictures)*.





HPM MURI Accomplishments:

Summary

DURIP Funding

- $ 141,087 for ns plasma diagnostics for pulse shortening studies, FY96.
- $ 125,095 for Hybrid Hard-Tube Driver for HPM, FY 97.
- $ 211,346 for state-of-the-art rf diagnostic instrumentation, FY99.

Publications on MURI project

- Over 20 Journal papers
- Over 20 Conference papers

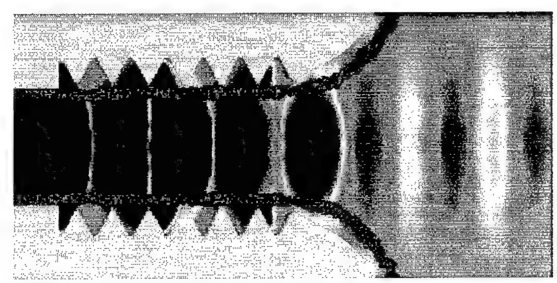
Workshop on High Power Microwave Sources and Technologies, hosted by UNM on June 3-12, 1999.

Personnel

- 3 Professors
- 3 Postdocs / Research Professors
- 6 Doctoral Students (1 AASERT)
- 5 Master Students
- 3 Undergraduate Students
- $^1/_2$ Laboratory Supervisor

IEEE Press Book

Advances in High Power Microwave Sources and Technologies



Edited by R.J. Barker and E. Schamiloglu, *IEEE Press*, 2001

University of Michigan

ABSTRACT SUMMARY OF ACHIEVED CONTRACT GOALS:

Experimental

1. Identified causes of microwave pulse shortening by time-frequency -analysis of signals and optical spectroscopy in gyrotrons,

2. Achieved microwave pulse-lengthening and increase of microwave pulse energy (15-245%) by plasma cleaning gyrotron,

3. Demonstrated polarization control in a rectangular cross section gyrotron,

4. Showed that coaxial gyrotrons exhibit higher current electron beam transport that non-coaxial tubes.

Theoretical

1. Revolutionized theory of multipactor,

2. Extended susceptibility diagram of multipactor due to oblique rf electric fields and rf magnetic fields,

3. Calculated for the first time the distribution of the impacting energy of the multipactoring electrons that is consistent with the space charge distribution at saturation,

4. Provided a scaling law for the resonant absorption of a finite electromagnetic pulse by the impurities on a dielectric.

SUMMARY OF EXPERIMENTALLY ACHIEVED CONTRACT GOALS AND RELATED SCIENTIFIC ACHIEVEMENTS

This research program was aimed at developing an understanding of the mechanisms for high power microwave generation and those effects that produce microwave pulse shortening. These experiments have been performed on the Michigan Electron Long Beam Accelerator, (MELBA) at parameters: V=-800 kV, I = 1-10 kA, and pulselength from 0.5-1 microsecond.

COAXIAL, SLOTTED GYROTRON OSCILLATOR

These experiments were directed towards investigation of which type of gyrotron cavity could operate most efficiently in a single mode:

1. Coaxial, unslotted gyrotron,

2. Coaxial gyrotron with slots, or

3. Non-coaxial, unslotted gyrotron.

The major finding was that the coaxial rod apparently raises the limiting electron beam current in the diode, causing higher current transport than the non-coaxial case. Electron current extraction from the non-coaxial gyrotron was erratic, believed due to the cathode current exceeding the vacuum limiting current in the diode region. The primary operating modes of this gyrotron were the TE111 and TE112. The peak microwave power levels generated were in the range of 40 MW for the coaxial, unslotted gyrotron with pulselengths up to 100 ns. Peak microwave emission reached 90 MW for the coaxial, slotted gyrotron, but the pulselengths were extremely short, 10-20 ns. The reason for these short pulselengths is postulated to be breakdown of the axial slots in the cavity. The non-coaxial cavity yielded lower microwave power levels of 20 MW, probably due to the lower electron current transport. Time-frequency-analysis (TFA) was performed on heterodyned microwave signals. These TFA computations demonstrated that gyrotron microwave pulse shortening mechanisms could be identified as:

1. E-beam voltage fluctuations causing frequency detuning away from the resonance,

2. Mode competition, and

3. Mode hopping.

Depending upon the magnetic tuning, these effects could be minimized.

HIGH POWER MICROWAVE PULSE-LENGTHENING AND ENERGY INCREASES BY PLASMA CLEANING A COAXIAL GYROTRON

This experimental effort on the coaxial gyrotron attacked the difficult problem of alleviating microwave pulse shortening. Temporally-resolved optical spectroscopy inside the operating gyrotron indicated that onset of hydrogen plasma was correlated to the decay time of the microwave power. Plasma is believed to absorb and reflect the microwaves in the collector region of the output waveguide. The source of the hydrogen is believed to be from water vapor adsorbed on the cavity/collector walls and coaxial rod. The new technique studied consisted of plasma cleaning of the interior of the gyrotron to sputter off and pump out the water prior to the microwave pulses.

The plasma cleaning technique utilized a radio-frequency generator at a frequency of 13.56 MHz. The rf power was coupled into the gyrotron through the coaxial rod at the microwave output window. Several different plasma cleaning protocols (gases, power levels and processing times) were tested, eventually utilizing a 50 W discharge power with nitrogen as the fill gas. The gas was pumped out by two cryo-pumps prior to the high power microwave pulse.

Experimental results showed that statistically significant increases in microwave pulse-length and energy (15-245%) occurred, depending upon the plasma cleaning time, from 5 minutes to over an hour (for the best case).

POLARIZATION CONTROL IN A RECTANGULAR CROSS SECTION GYROTRON

A series of experiments were performed to demonstrate the concept of a rectangular cross- section (RCS) gyrotron. This gyrotron has the advantages of linear polarization of the output radiation in either of two orthogonal modes (TE10 vs. TE01). The rectangular gyrotron principle would be critical to the concept of the active-circulator gyrotron traveling wave amplifier. The experiments showed that high power microwave polarization could be selected between the two orthogonal modes by changing only the solenoidal magnetic field. Polarization power ratios up to several hundred were achieved by this experiment. Peak microwave power levels were in the range of 14 MW in the TE10 mode and 6 MW in the TE01 mode. Electronic efficiencies reached 8%, with a 16% transverse efficiency. Polarization power ratios agreed qualitatively with the results of MAGIC code simulations.

BRIEF SUMMARY OF ACHIEVED CONTRACT GOALS (THEORY)

REVOLUTIONIZED THE THEORY OF MULTIPACTOR.

Multipactor has often been considered to be a major cause that triggers HPM pulse shortening, either by detuning the resonant structure sufficiently and/or stimulating desorption and subsequent plasma production in the output section. U of Michigan revolutionized the theory of multipactor, both on metallic surfaces and on dielectric.

TIME-FREQUENCY ANALYSIS

For the first time, we applied the time-frequency analysis, with unprecedented resolution, (1) to explicitly demonstrate frequency chirping in the HPM output signal, and (2) to explain it in terms of the temporal variations in the diode voltage. This opens up a new way to analyze mode hopping, mode competition, and to correlate pulse shortening to plasma production, etc., that are described in more detail in the experiments section.

COLLABORATION WITH AIR FORCE RESEARCH LAB

We collaborated closely with AFRL scientists in various HPM experiments. We provided the theoretical foundation of the AFRL injection-locked relativistic klystron amplifier. We derived a novel starting condition for the transit time oscillator which compared well with the AFRL simulations. We assessed the effects of beam loading in the RKO and MILO

experiments. We addressed simulation issues such as emission algorithms and electromagnetic transients. We constructed the 2-D Child-Langmuir Law.

Y.Y. LAU GUEST-EDITED THE IEEE TRANSACTIONS ON PLASMA SCIENCES, SPECIAL ISSUE ON HPM (6/1998 ISSUE).

MULTIPACTOR ON METAL

The susceptibility diagrams for the existence of multipactor for a wide class of metals are constructed. We found that multipactor in a resonant structure saturates by a combination of beam loading and detuning. The saturation levels and the transient buildups of multipactor were linked to materials properties for the first time. We discovered a novel phase mechanism whereby the multipactor electrons form a tight bunch in spite of their electrostatic repulsion. We analyzed the feasibility of multipactor suppression by means of an auxiliary signal.

MULTIPACTOR ON DIELECTRIC

The susceptibility diagram for the existence of multipactor for a wide class of dielectrics is constructed. The saturation levels, saturation mechanism, and the transient buildups of multipactor on an rf window were analyzed. It was found that saturation of multipactor is by space charge effects (and not by beam loading). At saturation, multipactor typically deposits about 2 per cent of the external rf power onto the rf window. Effects of oblique rf electric fields and of rf magnetic field were analyzed. We analytically determined the energy distribution of multipactor electrons that are consistent with their space charge. Close collaboration with Texas Tech and UC Berkeley were maintained throughout this project.

INTERPRETATION OF THE AFRL INJECTION-LOCKED RKO

In collaboration with AFRL scientists, we proposed a simple model which explained (and successfully predicted) the performance of the injection-locked RKO.

2-D CHILD LANGMUIR LAW

The classic 1-D Child-Langmuir Law was extended to 2-D through a synthesis of the results from PIC simulation.

BEAM-GAP INTERACTIONS

The starting condition for the Transit-Time-Oscillator was derived. It compared favorably with AFRL simulations. The effects of beam loading on RKO and on MILO were analyzed by the use of a simple model and compared with experimental data. [This project is still ongoing.]

FREQUENCY CHIRP IN HPM OUTPUT

A simple model was constructed that explains the frequency chirp in the gyrotron output signal in terms of the diode voltage fluctuation. This was made possible by the beautiful time-frequency analysis described more fully in the experimental section.

RESONANT ABSORPTION BY DIELECTRIC IMPURITIES

It was found that up to 60 per cent (or higher) of the rf pulse energy may be resonantly absorbed by a dielectric if (1) there is just a small concentration of impurities that have a resonant line at the rf frequency, and if (2) the pulse length is about 100 rf cycles. A scaling law has been constructed which might be useful to optical lithography in the semiconductor industry.

BEAM QUALITY IN A FIELD EMITTER ARRAY

A simple scaling law was constructed to assess the emittance of field emitters in terms of the geometry, gate voltage, and the Fowler-Nordheim coefficients A, B.

ABSOLUTE INSTABILITY IN TWT

The threshold current for the onset of absolute instability in TWT was derived.

Microwave Sciences, Inc

SUMMARY OF ACHIEVED CONTRACT GOALS

Pulse Shortening

Microwave Sciences Inc. (MSI) has concentrated on understanding and overcoming this key problem by gaining a more fundamental understanding of the physics of pulse shortening. In this work we have

1. Developed a general model for pulse shortening and compared to data from several varieties of sources, with good agreement.

2. Conducted a review of observations and theories of pulse shortening.

3. Identified the cause of pulse shortening in the relativistic magnetron by analyzing experiments.

4. Served as 'Chapter Master' for the Pulse Shortening chapter in the fourth-coming book "*Advances in High Power Microwave Source Research and Technologies*".

Transition to Better HPM Source Surface and Vacuum Conditions

1. Communicated "lessons learned" from hard-won experience on surface conditioning, bakeout, material selection and discharge cleaning methods and processes, with measurable but finite success.

Low-Closure-Rate Cathode Materials at High Electric Fields

1. Demonstrated CsI cathode, a low-closure material, which operates at electric fields high enough for the PS HPM sources.

2. Assisted the cathode work at PS and the oxide cathode work at UNM.

3. Located an industry source of Carbon-Carbon fiber fabrication that solves the problem of making a large-area, low outgassing, low closure-rate cathode compatible with high temperature. Communicated this information to AFRL and monitored progress in transitioning the technology to AFRL. This has recently resulted in better cathode performance and AFRL is now ordering and using much larger area cathodes made of the carbon-fiber material.

Vircator Studies

Consulted with the coaxial Vircator experiments at TTU and then continued a low level of work toward a virtode experiment, now planned for 2000 at TTU.

Microwave-Driven Propulsion

Explored a new area of interest to the Air Force [the primary interest at present is from NASA]. We have conducted modeling and experiments, have kept the AFRL informed of our work and may conduct an experiment at AFRL/Kirtland using their more powerful sources.

Summary of major related scientific achievements

- Identified the cause of pulse shortening in the relativistic magnetron
- Developed a general model for pulse shortening
- Demonstrated CsI cathode, a low-closure material which operates at electric fields high enough for the PS HPM sources.

SUMMARY OF HONORS/AWARDS

April 1995 – April 2000

Texas Tech University

Prof. M. Kristiansen is a Life Fellow of the Institute of Electrical and Electronics Engineers, a Fellow of the American Physical Society, and a Foreign Member of the Ural Branch of the Russian Academy of Sciences. He received the IEEE Millenium Medal awarded by the IEEE NPSS.

Prof. Osamu Ishihara was elected Fellow of the Institute of Electrical and Electronic Engineers, 1997.

Prof. L.L. Hatfield was appointed chairman of the Physics Department, 1999.

Dr. Jim Dickens was appointed an Assistant Professor in 1999.

Dr. Andreas Neuber was appointed an Assistant Professor in 2000.

University of New Mexico

Faculty Awards

Professor Schamiloglu:

University of New Mexico Regents' Lecturer (extra compensation for 996-1999, title for life) "...an Associate Professor for outstanding research contributions as well as excellence in teaching, scholarship, and service."

Promoted to Professor of Electrical and Computer Engineering and awarded the Gardner-Zemke Chair for 2000-2003.

Professor Abdallah:

Lawton-Ellis Award for Outstanding EECE Faculty 1999-2000 academic year.
IEEE Millenium Medal, awarded by local IEEE chapter.
Promoted to Professor of Electrical and Computer Engineering

Graduate Students Awards

Chris Grabowski:

Weizmann Fellowship to spend 2 years at the Weizmann Institute in Rehovot, Israel. Chris worked under Professor Yitzhak Maron to study plasma spectroscopy of pulsed power-driven plasma experiments (August 1998).

Robert Wright:
Outstanding Graduate Student in EECE, Fall 1998.

Fenghua Liu:
IEEE Travel Grant for ICOPS conference in 1999.

Mohammad Mojahedi:

Popejoy Award for best Ph.D. dissertation at UNM, 1999-2000
(co-advised by K.J. Malloy, co-supported by ARO)

University of Michigan

Faculty Awards

1. R.M. Gilgenbach was elected to Fellow of the American Physical Society Division of Plasma Physics in 1996.

2. R.M. Gilgenbach, Plasma Science and Applications Committee (PSAC) Award from IEEE in 1997

3. Y.Y. Lau, Research Excellence Award, UM College of Engineering, 1998

4. Y.Y. Lau, Plasma Science and Applications Committee (PSAC) Award from IEEE in 1999

5. R.M. Gilgenbach, Faculty Award from NERS Dept, 2000

Microwave Sciences

1. IEEE Fellow, 1996 The citation is "*For Development Of High Power Microwave Sources And For Transferring This Technology Into Custom Products.*"

2 EMP FELLOW, 1998 The citation is "*For Development Of HPM Sources.*"

LIST OF GRADUATE STUDENTS, TITLES OF THESES/DISSERTATIONS, AND CURRENT EMPLOYMENT

Texas Tech University

Ph.D. Students

1. Kevin Woolverton, Ph.D. in Electrical Engineering, May 1998, "High-Power, Coaxial Vircator Geometries". After graduation he was employed by Intel Corporation and is currently at Texas Tech University as a Research Associate.

2. John Mankowski, Ph.D. in EE, May 1998, "High Voltage Sub-nanosecond Dielectric Breakdown".
   He is currently employed at Accurate Automation Corp. in Chattanooga, TN.

3. Doug Young, Ph.D. in EE, May 1998, "Microwave Emission in a Plasma Filled Nonuniform Backward Wave Oscillator. He is currently at Mercer University, Macon, GA.

4. David Hemmert, MS in Physics, May 1998, "Window and Cavity Breakdown Caused by High Power Microwaves". Mr. Hemmert is a candidate for the Ph.D. degree in the Department of Electrical Engineering at Texas Tech University.

M.S. Students

1. Jason Elliott, MS in EE, May 1997, "Microwave Window Breakdown", employed by Raytheon in Richardson, Texas.

2. John Rybicki, Graduate Student in Electrical Engineering, experimental work on high power 10 GHz deflecting extended interaction Klystron. He left the university to accept an industrial job but is still enrolled at TTU to finish his master's thesis.

3. Kipp Axton, (AASERT) Graduate Student in Electrical Engineering, experimental work on high power 10 GHz deflecting extended interaction Klystron. He left the university to accept an industrial job but is still enrolled at TTU to finish his master's thesis.

4. Mohammed Suhail, Graduate Student in electrical Engineering. Experimental work on 10 GHz deflecting Klyston.

University of New Mexico

Ph.D. Students:

1. Larald Moreland, "Effects of Varying Coupling Impedance, Finite Length, and Asynchronous Harmonics on High Power BWO Performance," 1995.
   (Larry is with Lockheed-Martin in Denver)

2. Chris Grabowski, "Pulse Shortening and Plasma Filling Studies on a Long-Pulse, High Power Backward Wave Oscillator," 1997
   (Chris is a research staff member at Cornell University)

3. Mohammad Mojahedi, "Superluminal Group Velocities and Structural Dispersion," 2000
   (Mohammad is 0.5 research staff member at the Center for High Technology Materials at UNM, and 0.5 postdoctoral research associate at U.C. Berkeley in the physics department under Raymond Chiao)

4. Robert Wright, "A Radial Transit Time Oscillator," August 2000

The following students are ABD (All but dissertation)

5. Wei Yang, "Quantified Inequalities in Control"
   (Wei is working for International Game Technology in Reno, Nevada)

6. Tommy Cavazos, "Material Properties of Bulk Ferroelectrics in Pulsed Power Applications"
   (Tommy is working for Maxwell Technologies at AFRL/Kirtland AFB)

M.S. Students:

1. Vatche Soualian, "Control of Static Systems using Iterative Learning Methodologies with Applications to High Power Microwave Sources," 1998 (Vatche is working for National Instruments in Dallas, TX).

2. Todd Park, "Implementing Smart Tube Technology," 1999 (Todd is working for Microwave Instrumentation Technologies in Duluth, GA).

3. Fenghua Liu, "Electron Emission from Thin Film Ferroelectric Cathodes," 1999 (Fenghua is a Ph.D. student at Texas A&M University).

M.S. Students whose research will carryover into a New World Vistas Grant, but retains the MURI topic

4. Kelly Hahn, "Analysis of the Cross-Excitation Instability," 2001

5. Sam Choi, "A Compact Reltron HPM Source," 2001

University of Michigan

Ph.D. Students

1. Jonathan Hochman, M.S. and Ph.D., Thesis: "Microwave Emission of Large and Small Orbit Rectangular Gyrotron Devices", (defense on April 15, 1998); (employed by Raytheon)

2. Reginald Jaynes, M.S. and Ph.D., Thesis: "Generation of High Power Microwaves in a Large Orbit Coaxial Gyrotron, defended on January 17, 2000 (employed by Raytheon)

3. William Cohen, M.S. and Ph.D., Thesis: "Optical Spectroscopy and Effects of Plasma in High Power Microwave Gyrotron Experiments", Defended on May 10, 2000, (employed by GE Lighting)

4. L.K. Ang, M.S. and Ph.D., "Laser-Surface Interaction: Energy Absorption and Surface Structures," Defended in May, 1999, (Now at Los Alamos National Laboratory)

5. Rami Kishek, M.S. and Ph.D., "Interaction of Multipactor Discharge and RF Structures", Defended in April, 1997, (Now at U of Maryland, College Park)

6. John W. Luginsland Ph.D., "Design considerations of a novel two-beam accelerator", Defended in 1996, (Now employed by AFRL)

7. Agust Valfells, M.S. and Ph.D., "Multipactor Discharge: Frequency Response, Suppression, and Relation to Window Breakdown", Defended on April 10, 2000

8. Chris Peters, M.S. (4/30/98), "Application of Time-Frequency Analysis to High Power Microwave Source Analysis", Ph.D. expected 2000-01

M.S. Student

9. D. Vollers, M.S. EECS degree, (Officer at Air Force Research Laboratory, Phillips Site)

SUMMARY OF PUBLISHING ACTIVITIES, APRIL 1995 – 2000
(books, journal articles and conference proceedings papers)

Texas Tech University

Books

1. Advances in High Power Microwave Sources and Technologies, R.J. Barker (AFOSR) and E. Schamiloglu (University of New Mexico) (IEEE Press, New Jersey, 2001) A. Neuber (TTU) contributed as a chapter master.

Journal Articles

1. The Role of Outgassing in Surface Flashover Under Vacuum", A. Neuber, J. Dickens, H. Krompholz, and M. Kristiansen, accepted for publication is special issue on Pulsed Power in IEEE Transactions on Plasma Science, 2000.

2. "Microwave Magnetic Field Effects on High Power Microwave Window Breakdown", D. Hemmert, A. Neuber, J. Dickens, H. Krompholz, L.L. Hatfield and M. Kristiansen, accepted for publication in Special Issue on High Power Microwaves in IEEE Transactions on Plasma Science, 2000.

3. "High Power Microwave Generation by a Coaxial Virtual Cathode Oscillator", W. Jiang, K. Woolverton, J. Dickens, and M. Kristiansen, IEEE Transactions on Plasma Science, 27 5, 1538-1542, October 1999.

4. "Efficiency Enhancement of a Coaxial Virtual Cathode Oscillator", W. Jiang, J. Dickens, and M. Kristiansen, Trans. on Plasma Science, 27 5, 1543-1547, October 1999.

5. "Initiation of High Power Microwave Dielectric Interface Breakdown" A. Neuber, D. Hemmert, H. Krompholz, L. Hatfield, and M. Kristiansen, Journal of Applied Physics 86 3, 1724-1728, August 1999.

6. "Dielectric Surface flashover in Vacuum at 100 K", A. Neuber, M. Butcher, L.L. Hatfield, M. Kristiansen and H. Krompholz, IEEE Trans. Dielectric and electrical Insulation, 6 4, August 1999.

7. "Imaging of High-Power Microwave-Induced Surface Flashover", A. Neuber, D. Hemmert, J. Dickens, H. Krompholz, L. L. Hatfield, and M. Kristiansen: IEEE Trans. Plasma Sci. 27, 138-139, 1999.

8. "High Voltage Subnanosecond Breakdown", J. Mankowski, J. Dickens, and M. Kristiansen, IEEE Special Issue Transactions on Plasma Science, 26, 874-878, 1998.

9. "Window Breakdown Caused by High Power Microwaves", A. Neuber. J. Dickens, D. Hemmert, H. Krompholz, L.L. Hatfield and M. Kristiansen, IEEE Special Issue Transactions on Plasma Science, 26 3, 296-303, June 1998.

Conference Papers

1. "3-D PIC Simulation of a Coaxial Vircator", W. Jiang, (Nagaoka University of Technology), Jim Dickens and M. Kristiansen, 13th International Conference on High-Power Particle Beams, June 2000, Nagaoka, Japan.

2. "High-Power Microwave Generation by a Coaxial Vircator", W. Jiang (Nagaoka University of Technology), Jim Dickens and M. Kristiansen, 13th International Conference on High-Power Particle Beams, June 2000, Nagaoka, Japan.

3. "Dielectric/Gas Interface Breakdown Caused by High Power Microwaves", D. Hemmert, A. Neuber, H. Krompholz, L.L. Hatfield and M. Kristiansen, 13th International Conference on High-Power Particle Beams, June 2000, Nagaoka Japan.

4. "High Power Microwave Window Breakdown under Vacuum and Atmospheric Conditions", D. Hemmert, a. Neuber, J. Dickens, H. Krompholz, L.L. Hatfield and M. Kristiansen, SPIE's International Symposium on AeroSense, (Intense Microwave Pulsed VII", 24-28, April 2000, Orlando, FL.

5. "Surface Flashover in Liquid Nitrogen", M. Butcher, A. Neuber, H. Krompholz, L. L. Hatfield, and M. Kristiansen. *Conference on Electrical Insulation and Dielectric Phenomena*, Austin, TX, 654-657 Oct. 1999.

6. "Surface Flashover of Dielectrics Immersed in Super-Cooled Liquid Nitrogen",M. Butcher, A. Neuber, H. Krompholz, L. L. Hatfield, and M. Kristiansen, *12th IEEE Int. Pulsed Power Conference*, 450-453, 1999

7. "High-Power Microwave Generation by Coaxial Vircator", W. Jiang, K. Woolverton, J. Dickens, and M. Kristiansen, *12th IEEE International Pulsed Power Conference*, 194-197, 1999.

8. "High Voltage Subnanosecond Corona Inception", J. Mankowski, J. Dickens, M. Kristiansen, J. Lehr, W. Prather, and J. Gaudet, *12th IEEE International Pulsed Power Conference*, 1392-1395, 1999.

9. "The Role of Outgassing in Surface Flashover under Vacuum", A. Neuber, M. Butcher, H. Krompholz, L. L. Hatfield, and M. Kristiansen *12th IEEE Int. Pulsed Power Conference*, 441-445, 1999 (Invited Paper).

10. "A Theory of RF Window Failure", A. Valfells, K.K. Ang, Y.Y. Lau, and R.M. Gilgenbach (University of Michigan, Ann Arbor), R.A. Kishek (University of Maryland, College Park), J. Verboncoeur (UC, Berkeley), A. Neuber, H. Krompholz, L.L. Hatfield (Texas Tech University), APS, Div. of Plasma Physics, 1998, abstracts published in Bull. Am. Phys. Soc., vol. 43, No. 8, November 1998.

11. "Computer Simulations of Coaxial Vircators", Kevin Woolverton, M. Kristiansen and L.L. Hatfield, SPIE Conference, 145-152, San Diego, CA, July 27-August 1, 1997.

12. "Window and Cavity Breakdown Caused by High Power Microwaves", A. Neuber, J. Dickens, D. Hemmert, H. Krompholz, L.L. Hatfield and M. Kristiansen, Proc. of 11th Pulsed Power Conf., 135-140, 1997.

13. "Breakdown at Window Interfaces Caused by High Power Microwave Fields", J. Dickens, A. Neuber, D. Hemmert, H. Krompholz, L.L. Hatfield, and M. Kristiansen, International Workshop on High Power Microwave Generation and Pulse Shortening, Edinburgh, UK, 10-12 June 1997, to appear in IEEE Transactions on Plasma Science, special issue on High-Power Microwaves, 2000.

14. "High Voltage Subnanosecond Dielectric Breakdown", J. Mankowski, J. Dickens and M. Kristiansen, F.J. Agee, W. Prather, and J.M. Lehr, presented to International Workshop on High Power Microwave Generation and Pulse Shortening, Edinburgh, Scotland, June 10-12, 1997.

15. "A Subnanosecond High Voltage Pulser for the Investigation of Dielectric Breakdown," J. Mankowski, M. Kristiansen, and L. Hatfield, Proc. 11th International Pulsed Power Conf. pp. 549-554, 1997.

16. "Diode Polarity Experiments on a Coaxial Vircator", Kevin Woolverton, M. Kristiansen, and L.L. Hatfield, 11th International Pulsed Power Conference, 759-764, 1997.

17. "Nanosecond breakdown of Liquid Dielectrics", J. Mankowski, L. Hatfield, and M. Kristiansen, Proc. BEAMS '96, Prague, Czech Republic, 607-610 1996.

18. "Coaxial Vircator Source Development", Kevin Woolverton, M. Kristiansen, and L.L. Hatfield, BEAMS '96, Prague, Czech Republic, 469-472, 1996.

19. "A Review of Catastrophic Electromagnetic Breakdown for Short Pulse Widths", F.J. Agee, D.W. Scholfield, R.P. Copeland, T.H. Martin, J.J. Carroll, J.J. Mankowski, and L.L. Hatfield, Proc. SPIE 1996 International Symposium on Optical Science, Engineering and Instrumentation, pp. 172-182, 1996.

20. "Breakdown at Window Interfaces Caused by High Power Microwave Fields," J.C. Dickens, J. Elliott, L.L. Hatfield, M. Kristiansen, and H. Krompholz, SPIE 1996 International Symposium on Optical Science, Engineering, and Instrumentation, "Intense Microwave Pulses IV", Volume 2843, pg. 153, 1996.

21. "High Voltage Breakdown at Nanosecond Pulse Widths", J. Mankowski, M. Kristiansen, and L. Hatfield, AMEREM, Albuquerque, NM, May 27-31, 1996.

22. "Central University Research Consortium," M. Kristiansen, Edl Schamiloglu, Ron Gilgenbach, and Jim Benford, Proc. 10th IEEE Pulsed Power Conf., 80-85, 1995.

23. "Characterization of the UNM Long-Pulse BWO Experiment", C. Grabowski, J.M. Gahl, E. Schamiloglu (UMN) and O. Ishihara (TTU), Proc. of the 10th International Pulsed Power Conf., 717-732, 1995.

University of New Mexico

Books

1. Advances in High Power Microwave Sources and Technologies, R.J. Barker and E. Schamiloglu (IEEE Press, New Jersey, 2001,.

2. High Power Microwaves, 2nd Ed., J. Benford, J. Swegle, and E. Schamiloglu, (Institute of Physics Publishing, Bristol, UK, 2002).

Journal Articles

1. "Time Domain Detection of Superluminal Group Velocity Using Single Microwave Pulses," M. Mojahedi, E. Schamiloglu, F. Hegeler, G.T. Park, K. Agi, and K.J. Malloy, in preparation for submittal to Phys. Rev. E., 2000.

2. "Studies of Relativistic Backward Wave Oscillator Operation in the Cross-Excitation Regime," F. Hegeler, M. Partridge, E. Schamiloglu, and C.T. Abdallah, accepted and to appear in IEEE Trans. Plasma Sci., Special Issue on High Power Microwave Generation, June, 2000.

3. "Electron Emission from Thin-film Ferroelectric Cathodes," F. Liu and C.B. Fleddermann, Appl. Phys. Lett., vol. 76, 1618-1620, 2000.

4. "Iterative Learning Control Applications to High Power Microwave Tubes," V.S. Soualian, G.T. Park, C.T. Abdallah, and E. Schamiloglu, accepted (with revisions) IEEE Trans. Control Sys. Tech. (to appear 2000/2001).

5. "Frequency Domain Detection of Superluminal Group Velocity in a Distributed Bragg Crystal," M. Mojahedi, E. Schamiloglu, K. Agi, and K.J. Malloy, IEEE J. Quantum Electron, vol. 36, 418-424, 2000.

6. "Experimental Study of a High-Power Backward-Wave Oscillator Operating Far from the Upper Cutoff," E. Schamiloglu, Comment on J. Phys. Soc. Japan, vol. 68, 2147-2148, 1999.

7. "Integration of a Microstrip Patch Antenna with a Two-Dimensional Photonic Crystal Subtrate," K. Agi, K.J. Malloy, E. Schamiloglu, M. Mojahedi, and E. Niver, Electromagnetics, vol. 19, 277-290, 1999.

8. "Observation of the Cross-Excitation Instability in a Relativistic Backward Wave Oscillator," C. Grabowski, E. Schamiloglu, C.T. Abdallah, and F. Hegeler, Phys. Plasmas, vol. 5, 3490-3492, 1998.

9. "Towards Smart Tubes Using Iterative Learning Control," C.T. Abdallah, V.S. Soualian, and E. Schamiloglu, IEEE Trans. Plasma Sci., vol. 26., 905-911, 1998.

10."Initial Plasma-Filled Backward Wave Oscillator Experiments Using a Cathode-Mounted Plasma Prefill Source," C. Grabowski, J. Gahl, and E. Schamiloglu, IEEE Trans. Plasma Sci., vol. 25, 653-668, 1998.

11. "Electron Density Measurements During Microwave Generation in a High Power Backward Wave Oscillator," F. Hegeler, C. Grabowski, and E. Schamiloglu, IEEE Trans. Plasma Sci., vol. 26, 275-281, 1998.

12. "Ferroelectric Sources and Their Application to Pulsed Power: A Review," C.B. Fleddermann and J.A. Nation, IEEE. Trans. Plasma Sci., vol. 25, 212-220, 1997.

13. "Electron Emission from Slow-Wave Structure Walls in a Long-Pulse, High-Power Backward Wave Oscillator," C. Grabowski, J.M. Gahl, and E. Schamiloglu, IEEE Trans. Plasma Sci., vol. 25, 335-341, 1997.

14. "Effects of the Forward Propagating Wave on the Efficiency of Relativistic Backward Wave Oscillators," S.D. Korovin, S.D. Polevin, A.M. Roitman, V.V. Rostov, L.D. Moreland, and E. Schamiloglu, Izvestiya Vysshikh Uchebnykh Zavedenii, Fizika, vol. 39, 49-55, 1996 (in Russian).

15. "Photonic Crystals: A New Quasi-optical Component for High Power Microwaves," K. Agi, L.D. Moreland, E. Schamiloglu, M. Mojahedi, K.J. Malloy, and E.R. Brown, IEEE Trans. Plasma Sci., vol. 24, 1067-1071, 1996.

16. "A Neural Network Model of the Input/Output Characteristics of a High Power Backward-Wave Oscillator," C. Abdallah, W. Yang, E. Schamiloglu, and L.D. Moreland, IEEE Trans. Plasma Sci., vol. 24, 879-883, 1996.

17. "Enhanced Frequency Agility of High Power Relativistic Backward Wave Oscillators," L.D. Moreland, E. Schamiloglu, R.W. Lemke, A.M. Roitman, S.D. Korovin, and V.V. Rostov, IEEE Trans. Plasma Sci., vol. 24, 852-858, 1996.

18. "High Power Microwave-Induced TM_{01} Plasma Ring," E. Schamiloglu, R. Jordan, M.D. Haworth, L.D. Moreland, I.V. Pegel, and A.M. Roitman, IEEE Trans. Plasma Sci., vol. 24, 6-7, 1996, 3.

19."Efficiency Enhancement of High Power Vacuum BWOs Using Nonuniform Slow Wave Structures," L.D. Moreland, E. Schamiloglu, R.W. Lemke, S.D. Korovin, V.V. Rostov, A.M. Roitman, K.J. Hendricks, and T.A. Spencer. IEEE Trans. Plasma Sci., vol. 22, 554-565, 1994.

Conference Papers

1. "Experimental Studies of the Cross-Excitation Instability in a Relativistic Backward Wave Oscillator," E. Schamiloglu, F. Hegeler, M. Partridge, C.T. Abdallah, and N. Islam, submitted to Intense Microwave Pulses VII, SPIE AeroSense 2000, Orlando, FL, April 2000 (in press).

2. "X-band Resistive Sensors for Short High-Power Microwave Pulse Monitoring," M. Dagys, Z. Kancleris, R. Simniskis, E. Schamiloglu, and F.J. Agee, Proc. 29th European Microwave Conference, Munich, Germany, p. 65-68, October 1999.

3. "Detection of Superluminal (but Causal) Group Velocity in One-Dimensional Photonic Crystals using a High Power Microwave Source" E. Schamiloglu, M. Mojahedi, F. Hegeler, G.T. Park, K. Agi, and K.J. Malloy, (Plenary Session Paper), Digest 24th International Conference on Infrared and Millimeter Waves, Monterey, CA, September 1999.

4. "Electron Emission from Ferroelectric Thin Film Cathodes, F. Liu and C.B. Fleddermann," Proc. 12th IEEE International Pulsed Power Conference, Monterey, CA, 1305-1308, 1999.

5. "Comparison of Theory and Simulation for a Radially Symmetric Transit-Time Oscillator," J.W. Luginsland, R.L. Wright, and E. Schamiloglu, Proc. 12th IEEE International Pulsed Power Conference, Monterey, CA, 859-862, 1999.

6. "Application of Resistive Sensors for Short High-Power Microwave Pulse Measurement," M. Dagys, Z. Kancleris, R. Simniskis, E. Schamiloglu, and F.J. Agee, Proc. 12th IEEE International Pulsed Power Conference, Monterey, CA, 829-832, 1999.

7. "Recent Advances in the Study of a Long Pulse Relativistic Backward Wave Oscillator," F. Hegeler, E. Schamiloglu, S.~D. Korovin, and V.~V. Rostov, Proc. 12th IEEE International Pulsed Power Conference, Monterey, CA, 825-828, 1999.

8. "Advances in the Control of a Smart Tube High Power Backward Wave Oscillator," G.T. Park, V.S. Soualian, C.T. Abdallah, E. Schamiloglu, and F. Hegeler, Proc. 12th IEEE International Pulsed Power Conference, Monterey, CA, 852-855, 1999.

9. "Recent Results from a Long Pulse, Relativistic Vacuum and Plasma-Filled Backward Wave Oscillator Experiment," E. Schamiloglu, F. Hegeler, C. Grabowski, and D. Borovina, Proc. Beams'98, Haifa, Israel, 869-872, 1998.

10. "An Ultra Wideband Photonic Crystal Antenna," K. Agi, M. Mojahedi, K.J. Malloy, and E. Schamiloglu, Proc. 11th IEEE International Pulsed Power Conference, Baltimore, MD, 753-758, 1997.

11. "Implementation of a Frequency-Agile, High Power Backward Wave Oscillator," E. Schamiloglu, C.T. Abdallah, G.T. Park, and V.S. Soualian, Proc. 11th IEEE International Pulsed Power Conference, Baltimore, MD, 742-746, 1997.

12. "A Cathode Mounted Plasma Prefill Source for High Power Microwave Experiments," C. Grabowski, J.M. Gahl, and E. Schamiloglu, Proc. 11th IEEE International Pulsed Power Conference, Baltimore, MD, 747-752, 1997.

13. "Initial Engineering Design for the Implementation of a Frequency-Agile, High Power Backward Wave Oscillator, " E. Schamiloglu, C.T. Abdallah, G.T. Park, and V.S. Soualian, Proc. International Workshop on High Power Microwave Generation and Pulse Shortening, Edinburgh, UK, 233-237, 1997.

14. "Initial Plasma-Filled BWO Results using a Novel Cathode Mounted Plasma Injection System," C. Grabowski, J.M. Gahl, and E. Schamiloglu, Proc. International Workshop on High Power Microwave Generation and Pulse Shortening, Edinburgh, UK, 9-14, 1997.

15. "On the Control of a High Power Backward-Wave Oscillator Using Quantifier Elimination Methods," C.T. Abdallah, W. Yang, V. Soualian, and E. Schamiloglu, Proc. American Control Conference, Albuquerque, NM, 3255-3256, 1997.

16. "Ultrawideband Photonic Crystal Antennas," K. Agi, M. Mojahedi, E. Schamiloglu, and K. Malloy, Proc. Seventh Annual DARPA Symposium on Photonic Systems for Antenna

17. "Pulse Shortening in High Power Backward Wave Oscillators," C. Grabowski, J.M. Gahl, and E. Schamiloglu, Proc. SPIE, Intense Microwave Pulse IV, vol. 2843, 251-259, 1996.

18. "Approaches to Achieving High Efficiency, Long Pulse, Vacuum Backward Wave Oscillator Operation," E. Schamiloglu, J. Gahl, C. Grabowski, and C. Abdallah, Proc. Beams '96, Institute of Plasma Physics, Czech Academy of Sciences, Prague, 433-436, 1996.

19. "Investigation of Electron Emission from Bulk Ferroelectric Ceramic Materials," T. Cavazos, D. Shiffler, and C.B. Fleddermann, Proc. 10th IEEE International Pulsed Power Conference, 699-704, 1995.

20. "Central University Research Consortium," M. Kristiansen, E. Schamiloglu, R. Gilgenbach, and J. Benford, Proc. 10th IEEE International Pulsed Power Conference, 80-85, 1995.

21. "Identification and Control Methods for High Power Electron Beam-Driven Microwave Tubes," C. Abdallah, W. Yang, E. Schamiloglu, and L. Moreland, Proc. 10th IEEE International Pulsed Power Conference, 711-716, 1995.

22. "Characterization of the UNM Long Pulse BWO Experiment," C. Grabowski, J.M. Gahl, E. Schamiloglu, and O. Ishihara, Proc. 10th IEEE International Pulsed Power Conference, 717-722, 1995.

23. "Effects of End Reflections on the Performance of Relativistic Backward Wave Oscillators," L.D. Moreland, E. Schamiloglu, and R.W. Lemke, Proc. 10th IEEE International Pulsed Power Conference, 705-710, 1995.

24. "A high Power Microwave Generator Based on a Relativistic BWO," A.M. Roitman, S.D. Korovin, S.D. Polevin, V.V. Rostov, E. Schamiloglu, and L.D. Moreland, Proc. SPIE, Intense Microwaves III, vol. 2557, 422-432, 1995.

UNIVERSITY OF MICHIGAN

JOURNAL ARTICLES

1. "Long Pulse, High Power, Large-Orbit, Coaxial Gyrotron Oscillator Experiments", R.L. Jaynes, R.M. Gilgenbach, C.W. Peters, W.E. Cohen M.R. Lopez, Y.Y. Lau, W.J. Williams, and Thomas A. Spencer, in press for IEEE Trans. Plasma Science.

2. "Effects of an External Magnetic Field, and of Oblique Radio-Frequency Electric Fields on Multipactor Discharge on a Dielectric, A. Valfells, L.K. Ang, Y.Y. Lau, and R.M. Gilgenbach, Physics of Plasmas 7 750 (Feb. 2000).

3. "Resonant Absorption of a Short-Pulse Laser in a Doped Dielectric", L.K. Ang, Y.Y. Lau, and R.M. Gilgenbach, Applied Physics Letters, 74, 2912 May 17, 1999.

4. "Velocity Ratio Measurement Diagnostics and Simulations of a Relativistic Electron Beam in an Axis Encircling Gyrotron", R.L. Jaynes, RM. Gilgenbach, J.M. Hochman, et al, in the Special Issue on Images in Plasma Science, 27, p. 136-138, Feb. 1999.

5. "Time-Frequency Analysis of Modulation of High Power Microwaves by Electron-Beam Voltage Fluctuations", C. W. Peters, R.L. Jaynes, Y.Y. Lau, R.M. Gilgenbach, W.J. Williams, J.M. Hochman, W.E. Cohen, J.I. Rintamaki, D.E. Vollers, J. Luginsland and T.A. Spencer, Phys. Rev. E, 58 6880 (November 1998).

6. "Optical Spectroscopy of Plasma in High Power Microwave Pulse Shortening Experiments Driven by a microsecond e-Beam", R.M. Gilgenbach, J.M. Hochman, R.L. Jaynes, W.E. Cohen, J.I. Rintamaki, C.W. Peters, D.E. Vollers, Y.Y. Lau, and T.A. Spencer, IEEE Transactions on Plasma Science, Special Issue on High Power Microwaves,26 282 (1998).

7. "Polarization Control of Microwave Emission from High Power Rectangular Cross Section Gyrotron Devices", J.M. Hochman, R.M. Gilgenbach, R.L. Jaynes, J.I. Rintamaki, Y.Y. Lau, W.E. Cohen, C. Peters, and T.A. Spencer, IEEE Transactions on Plasma Science, Special Issue on High Power Microwaves, 26 383 (1998).

8. "Power Deposited on a Dielectric by Multipactor", L.K. Ang, Y.Y. Lau, R.A. Kishek, and R.M. Gilgenbach, IEEE Transactions on Plasma Science, Special Issue on High Power Microwaves, 26 290 (1998).

9. "Multipactor Discharge on Metals and Dielectrics: Historical Review and Recent Theories", R.A. Kishek, Y. Y. Lau, L.K. Ang, A. Valfells, and R.M. Gilgenbach, Physics of Plasmas, 5 2120 (1998).

10. "2-D Child Langmuir Law", J. Luginsland, Y.Y. Lau, and R.M. Gilgenbach, Physical Review Letters, 77, pp. 4668-4670 (1996).

11. "A Novel Phase Focusing Mechanism in Multipactor Discharge", R. A. Kishek and Y. Y. Lau, Phys. Plasmas, 3, 1481 (1996).

12. "An Evaluation of the Intrinsic Emittance of a Field Emitter", Youfan Liu and Y. Y. Lau, J. Vac. Sci. Technol. B14, 2126 (1996).

13. "Steady State Multipactor and Dependence on Material Properties", R. A. Kishek, Y. Y. Lau, and D. Chernin, Phys. Plasmas 4, 863 (1997).

14. "High Power Transit Time Oscillator: Onset of Oscillation and Saturation", J. W. Luginsland, M. J. Arman, and Y. Y. Lau, Phys. Plasmas 4, 4404 (1997).

15. "Multipactor Discharge on a Dielectric", R. A. Kishek and Y. Y. Lau, Phys. Rev. Lett. 80, 193 (1998).

16. "Frequency Response in Multipactor Discharge", A. Valfells, R. A. Kishek, and Y. Y. Lau, Phys. Plasma 5, 300 (1998).

17. "Virtual Cathode Formation due to Electromagnetic Transients", J. W. Luginsland, S. McGee, and Y. Y. Lau, IEEE Trans. Plasma Sci. 26, 901 (1998).

18. "Absolute Instability in a Traveling Wave Tube Model", L. K. Ang and Y. Y. Lau, Phys. Plasmas 5, 4408 (1998).

19. "A Model for Injection-Locked Relativistic Klystron Oscillator", J. W. Luginsland, Y. Y. Lau, K. J. Hendricks, and P. D. Coleman, IEEE Trans. Plasma Sci 24, 935 (1996).

Conference Papers

1. "Multipactor Discharge and RF Window Failure", Bulletin of the American Physical Society", Rex Anderson, A. Valfells, L.K. Ang, Y.Y. Lau, R.M. Gilgenbach, J. Verboncoeur, A. Neuber, H. Krompholz; vol. 44, No. 7, Nov. 1999; at APS Division of Plasma Physics Annual Meeting, Nov. 15-19, 1999 Seattle, WA

2. "Effects of Magnetic Fields, and of Oblique RF Electric Fields on Susceptibility to Multipactor Discharge on a Dielectric", A. Valfells, L.K. Ang, Y.Y. Lau, R.M. Gilgenbach; Bulletin of the American Physical Society vol. 44, No. 7, Nov. 1999; at APS Division of Plasma Physics Annual Meeting Nov. 15-19, 1999 Seattle, WA

3. "Time-Frequency Analysis of High Power Microwaves Using Discrete Prolate Spherical Sequences", C.W. Peters, R.M. Gilgenbach, W.J. Williams, Y.Y. Lau, R.L. Jaynes, W.E. Cohen, M.R. Lopez, T.A. Spencer; Bulletin of the American Physical Society, vol. 44, No. 7, Nov. 1999; at APS Division of Plasma Physics Annual Meeting, Nov. 15-19, 1999 Seattle, WA

4. "Comparison of Slotted and Unslotted Multi-MW Large Orbit, Axis-Encircling, Coaxial Gyrotron Oscillators ", R.L. Jaynes, R.M. Gilgenbach, C.W. Peters, W.E. Cohen, M.R. Lopez, J.M. Hochman, Y.Y. Lau, T.A. Spencer; Bulletin of the American Physical Society vol. 44, No. 7, Nov. 1999; at APS Division of Plasma Physics Annual Meeting; Nov. 15-19, 1999 Seattle, WA

5. "Plasma Processing and Optical Emission Spectroscopy in High Power Microwave Pulse Shortening Experiments", W.E. Cohen, R.M. Gilgenbach, R.L. Jaynes, C.W. Peters, M.R. Lopez, J.I. Rintamaki, Y.Y. Lau , T.A. Spencer; Bulletin of the American Physical Society vol. 44, No. 7, Nov. 1999; at APS Division of Plasma Physics Annual Meeting Nov. 15-19, 1999 Seattle, WA

6. "Resonant Absorption of a Short-Pulse Laser in a Doped Dielectric", L.K. Ang, Y.Y. Lau, R.M. Gilgenbach, B. Qi; Bulletin of the American Physical Society, vol. 44, No. 7, Nov. 1999 ; at APS Division of Plasma Physics Annual Meeting Nov. 15-19, 1999 Seattle, WA

7. "Resonant Absorption of a Short Electromagnetic Pulse", L.K. Ang, Y. Y. Lau, and R. M. Gilgenbach, 40th Annual Meeting of the APS Division of Plasma Physics, Nov. 16-20, 1998, New Orleans, LA, abstracts published in Bull. Am. Phys. Soc. vol. 43, No. 8, Nov. 98

8. "A Theory of RF Window Failure", A. Valfells, L. K. Ang, Y. Y. Lau, R.M. Gilgenbach, R. A. Kishek, J. Verboncoeur, A. Neuber, H. Krompholz, L. L. Hatfield, 40th Annual Meeting of the APS Division of Plasma Physics, Nov. 16-20, 1998, New Orleans, LA, abstracts published in Bull. Am. Phys. Soc. vol. 43, No. 8, Nov. 98

9. "Absolute Instability in a TWT", Y. Y. Lau, L. K. Ang, 40th Annual Meeting of the APS Division of Plasma Physics, Nov. 16-20, 1998, New Orleans, LA, abstracts published in Bull. Am. Phys. Soc. vol. 43, No. 8, Nov. 98

10. "Optical Spectroscopy of Plasma and Plasma Processing in High Power Microwave Pulse Shortening Experiments", W.E. Cohen, R.M. Gilgenbach, R. L. Jaynes, J. I. Rintamaki, C. W. Peters, J. M. Hochman, D. E. Vollers, Y. Y. Lau, 40th Annual Meeting of the APS Division of Plasma Physics, Nov. 16-20, 1998, New Orleans, LA, abstracts published in Bull. Am. Phys. Soc. vol. 43, No. 8, Nov. 98

11. "Laser-Heated Lanthanum-Hexaboride Cathode for Long-Pulse Electron Beam Generation", D.E. Vollers, R.M. Gilgenbach, R.L. Jaynes, M.D. Johnson, W.D. Getty, J.M. Hochman, W.E. Cohen, J.I. Rintamaki, C. W. Peters and T.A. Spencer, 40th Annual Meeting of the APS Division of Plasma Physics, Nov. 16-20, 1998, New Orleans, LA, abstracts published in Bull. Am. Phys. Soc. vol. 43, No. 8, Nov. 98

12. "Joint Time-Frequency Analysis of High Power Microwave Signals", C. W. Peters, R.L. Jaynes, Y.Y. Lau, R.M. Gilgenbach, W.J. Williams, J.M. Hochman, W.E. Cohen, J.I. Rintamaki, D.E. Vollers, J. Luginsland and T.A. Spencer, 40th Annual Meeting of the APS Division of Plasma Physics, Nov. 16-20, 1998, New Orleans, LA, abstracts published in Bull. Am. Phys. Soc. vol. 43, No. 8, Nov. 98.

13. "Multi-MW Large Orbit, Axis-Encircling, Coaxial Gyrotron Oscillator Experiments", R. L. Jaynes, R. M. Gilgenbach, C. W. Peters, W. E. Cohen, J. I. Rintamaki, D. E. Vollers, J. M. Hochman, Y. Y. Lau, 40th Annual Meeting of the APS Division of Plasma Physics, Nov. 16-20, 1998, New Orleans, LA, abstracts published in Bull. Am. Phys. Soc. vol. 43, No. 8, Nov. 98.

14. "Multipactor Discharge", R. A. Kishek, D. Chernin, and Y. Y. Lau, presented in the Joint Meeting of the Int'l Radio Union and IEEE Society of Antenna and Propagation (Montreal, Canada, (1997).

15. "Multipactor, in the International Workshop on Crossed-Field Devices and Applications, Y. Y. Lau, R. A. Kishek, L. K. Ang, and R. M. Gilgenbach, Boston, MA (June, 1998).

16. "Electromagnetic Limiting Current", J. W. Luginsland, S. McGee, and Y. Y. Lau, in SPIE Proc., Intense Microwave Pulses V, Vol. 3158 (1997).

17. "Multipactor Discharge on RF window", Y. Y. Lau, L. K. Ang, R. A. Kishek, and R. M. Gilgenbach, presented in the Monterey RF Vacuum Electronics Conference (May, 1998).

18. "Multipactor Discharge on Dielectric", Y. Y. Lau, R. A. Kishek, L. K. Ang, A. Valfells, and R. M. Gilgenbach, Bulletin American Society, April, 1998 (Ohio APS Meeting).

19. "Multipactor Discharge", Invited Paper, R.A. Kishek, at the American Physical Society Meeting, Pittsburgh, 1998.

20. "Disruption of Electron Flows in a Crossed-Field Gap by a Slight Misalignment in the Magnetic Field", A.L. Garner, Y.Y. Lau and D. Chernin, presented at the 1997 American Physical Society Division of Plasma Physics Meeting, Pittsburgh, PA, Nov. 17-21, 1997.

21. "Polarization Control of High Power Microwave Emission from a Large Orbit, Rectangular Cross Section Gyrotron", J.M. Hochman, R.M. Gilgenbach, R.L. Jaynes, J.I. Rintamaki, W.E. Cohen, C. Peters, Y.Y. Lau and T.A. Spencer, presented at the 1997 American Physical Society Division of Plasma Physics Meeting, Pittsburgh, PA, Nov. 17-21, 1997.

22. "Suppression of Multipactor Discharge by an Auxiliary RF Signal", A. Valfells, R. Kishek, Y.Y. Lau and R.M. Gilgenbach, presented at the 1997 American Physical Society Division of Plasma Physics Meeting, Pittsburgh, PA, Nov. 17-21, 1997.

23. "Multipactor Discharge on a Dielectric", Y.Y. Lau, R. Kishek, L.K. Ang and R.M. Gilgenbach, presented at the 1997 American Physical Society Division of Plasma Physics Meeting, Pittsburgh, PA, Nov. 17-21, 1997

24. "Optical Spectroscopy of Plasma in a High Power Gyrotron", W.E. Cohen, R.M. Gilgenbach, J.M. Hochman, R.L. Jaynes, J.I. Rintamaki, C.W. Peters, Y.Y. Lau and T.A. Spencer,

presented at the 1997 American Physical Society Division of Plasma Physics Meeting, Pittsburgh, PA, Nov. 17-21, 1997

25. "Diagnostic Experiments and Simulations of a Large Orbit Rectangular Cross Section Gyrotron", R.L. Jaynes, R.M. Gilgenbach, J.M. Hochman, J.I. Rintamaki, W.E. Cohen, Y.Y. Lau, C. Peters and T.A. Spencer, presented at the 1997 American Physical Society Division of Plasma Physics Meeting, Pittsburgh, PA, Nov. 17-21, 1997

26. "Rectangular Cross Section Gyrotron", J.M. Hochman, R.M. Gilgenbach, R. Jaynes, J.I. Rintamaki, Y.Y. Lau, J. Luginsland, and J.S. Lash, presented and published in Proceedings of SPIE's Intense Microwave Pulses IV, Denver, CO, 4-9, August 1996

27. "High Power Microwave Emission and Diagnostics of Microsecond Electron Beams", R.M. Gilgenbach, J.M. Hochman, R. Jaynes, J.I. Rintamaki, Y.Y. Lau, J. Luginsland, and J.S. Lash, presented and published in Proceedings of the 11th International Conference on High Power Beams, Prague, Czech Republic, June 10-14, 1996

28. "An Analysis of Multipactor in an External Magnetic Field", A. Valfells, R. Kishek, Y.Y. Lau, R.M. Gilgenbach, Thirty-Eighth APS-DPP Annual Meeting, Bulletin of APS, 41 1391 (1996)

29. "Steady State Multipactor and Dependence on Material Properties", R. Kishek, Y.Y. Lau, R.M. Gilgenbach, D.P. Chernin, Thirty-Eighth APS-DPP Annual Meeting, Bulletin of APS, 41 1391 (1996)

30. "Diagnostic Experiments and Simulation for Relativistic Electron Beams in Axially Varying Magnetic Fields for Applications to Gyrotrons", R. Jaynes, R.M. Gilgenbach, J. Hochman, J. Rintamaki, Y.Y. Lau, and T.A. Spencer, Thirty-Eighth APS-DPP Annual Meeting, Bulletin of APS, 41 1391 (1996)

31. "High Power Microwave Emission of Large and Small Orbit Gyrotron Devices in Rectangular Interaction Structures", J. Hochman, R.M. Gilgenbach, R. Jaynes, J. Rintamaki, J. Luginsland, YY. Lau, T. A. Spencer, Thirty-Eighth APS-DPP Annual Meeting, Bulletin of APS, 41 1391 (1996)

32. "Rectangular Interaction Structures in High Power Gyrotron Devices", R.M. Gilgenbach, J.M. Hochman, R. Jaynes, M.T. Walter, J. Rintamaki, J.S. Lash, J. Luginsland, Y.Y. Lau, and T.A. Spencer, Conference Digest of Twentieth Infrared and Millimeter Waves Conference, December 1995, Orlando, FL

MICROWAVE SCIENCES, INC.

Journal Articles

1. "Significant Pulse-Lengthening in a Multigigawatt Magnetically Insulated Transmission Line Oscillator", K. Hendricks, J. Benford, *et al.*, IEEE Trans. on Plasma Sci., **26**, pg. 312 (1998).

2. "Diode plasma effects on the microwave pulse length from relativistic magnetrons", D. Price, J. Benford and J. S. Levine, IEEE Trans. on Plasma Sci., **26**, pg. 348 (1998).

3. "General Scaling of Pulse Shortening in Explosive-Emission-Driven Microwave Sources", D. Price and J. Benford, IEEE Trans. on Plasma Sci., **26**, pg. 256 (1998).

4. "Recent Progress in the Hard-Tube MILO Experiment", M. Haworth, J. Benford, *et al.,* SPIE **3158**, pg. 28 (1997).

5. "Survey of Pulse Shortening in High Power Microwave Sources", J. Benford and G Benford, IEEE Trans. on Plasma Sci., **25**, 311 (1997).

6. "Microwave Bream-driven Propulsion Experiments for High-Speed Space Exploration", James Benford, Henry Harris, Gregory Benford, and Timothy Knowles, to be published.

Conference Papers

1. "Pulse Shortening in High Power Microwave Sources", J. Benford, D. Price and G. Benford, Beams '96, ISBN 80-9092250-3-9, Vol 1, 217 (1996).

2. "Pulse Shortening in High Power Microwave Sources", J. Benford and G. Benford Proceedings of Edinburgh Workshop, Edinburgh UK, (1997).

3. "Pulse Shortening in High Power Microwave Sources", J. Benford, Proceedings of 11th IEEE Int'l Pulsed Power Conf, Baltimore MD, (1997).

4. "ORION- A Frequency-Agile HPM Field Test System", J. Benford, D. Price and J. S. Levine, Seventh National Conference on High Power Microwave Technology, Laurel, MD (1997).

5. "Lowered Plasma Velocity with Cesium Iodide/Carbon Fiber Cathodes at High Electric Field", J. Benford , David Price and William DeHope, Beams '98, vol. 2, pg. 695, (1998).

6. "General Scaling of Pulse Shortening in Explosive-Emission-Driven Microwave Sources ", with David Price, Beams '98, vol. 2, pg. 691, (1998).

7. "High-Power Microwaves at 25 Years: The Current State of Development", with John Swegle, Proc. Beams '98, vol. 1, pg. 149, (1998).

Post Conference Presentations

1. "Microwave Beam-driven Propulsion Experiments for High-Speed Space Exploration", James Benford, Henry Harris, Gregory Benford, and Timothy Knowles EuroEM, May 30-June 2, 2000, Edinburgh, Scotland [Talk].

2. Microwave Beam-Driven Sail Flight Experiments", James Benford, Henry Harris, Gregory Benford, Timothy Knowles, Keith Goodfellow and Raul Perez, Eleventh Advanced Space Propulsion Research Workshop (APC2000), Pasadena, CA, May 29-June 2, 2000 [Invited Talk, to be given by Gregory Benford].

INTRODUCTION

This progress report is part of the inclusive final report and covers the last period of this contract from 1 September 1999 to contract expiration, 14 April 2000. The publication-lists for this period include their associated abstracts and these publications were included in the final report citation listings.

CONSORTIUM PERSONNEL

TEXAS TECH UNIVERSITY

Professor M. (Kris) Kristiansen, Principal Investigator and Consortium Director

Tasks

- **Microwave Vacuum and Window Breakdown**
  - Prof. Lynn L. Hatfield (directs laboratory research)
  - Prof. Hermann G. Krompholz (directs laboratory research)
  - Dr. James Dickens (conducts laboratory research)
    Microwave experiment design and modeling of microwave systems
  - Dr. Andreas Neuber (conducts laboratory research)
  - David Hemmert, Graduate Student in Physics, graduated with MS degree in Physics in May 1998 and continues for Ph.D. degree in Electrical Engineering

- **Ultrawideband Microwave Generation**
  - Prof's. H. Krompholz and Lynn L. Hatfield (direct laboratory research)
  - Cooperative studies with J. Lehr, AFRL, Phillips Site.

- **Alternate Geometry Vircators**
  - Prof. M. Kristiansen and Prof. Lynn L. Hatfield (direct laboratory research).

- **Advances in high Power Microwave Sources and technologies, IEEE Press (AFOSR/MURI)**
  - Professor Edl Schamiloglu (UNM, co-editor)
  - Dr. Robert J. Barker (AFOSR, co-editor)
  - Dr. Andreas Neuber (TTU, contributed chapter to book)

UNIVERSITY OF NEW MEXICO

Professor Edl Schamiloglu, Principal Investigator

NOTE: Personnel listed below covers only those research topics we have worked on 1 September 1999 - 15 April 2000

Tasks

- **Hybrid Hard Tube BWO**
  (AFOSR/MURI and DURIP'96, DURIP'97, and DURIP'99 awards)
  - Professor Edl Schamiloglu (directs research)
  - Dr. Frank Hegeler (laser diagnostics and hybrid hard tube)
  - Professor Chaouki Abdallah (time-frequency analysis)
  - Kelly Hahn (cathode design for BWO)

- **Long Pulse Intense Beam BWO: Cross-Excitation Instability**
  AFOSR/MURI and DURIP'99 awards)
  - Professor Edl Schamiloglu (directs research)
  - Dr. Frank Hegeler (experiments)
  - Professor Chaouki Abdallah (time-frequency analysis)
  - Michael Partridge (M.S. candidate)
  - Kelly Hahn (M.S. candidate)

- **Radial Acceletron Transit Time Oscillator**
  (AFOSR/MURI/AASERT/AFRL)
  - Professor Edl Schamiloglu (directs research)
  - Robert Wright (Ph.D. candidate)
  - Drs. Mo Arman, John Luginsland, Kyle Hendricks, Tom Spencer, Diana Loree, and Sgt. Walt Fayne (all AFRL/Phillips)

- **Educational Reltron HPM Source**
  (AFOSR/MURI/DURIP'96)
  - Professor Edl Schamiloglu (directs research)
  - Dr. R. Bruce Miller (LANL, also consultant to Titan/PSI)
  - Sam Choi (M.S. candidate)

- **HPM Characterization of Photonic Crystals**
  (AFOSR/MURI, ARO, and AFRL)
  - Professors Edl Schamiloglu and Kevin Malloy (direct research)
  - Dr. Frank Hegeler (experiments)
  - Dr. Kamil Agi (experiments)
  - Mohammad Mojahedi (Ph.D. candidate)

- **Resistive Sensor for HPM Measurement**
  (AFOSR/EOARD)
  - Professor Edl Schamiloglu and Dr. Jack Agee (AFOSR)
  - Dr. Frank Hegeler
  - Drs. Mindagys Dagys and Zilvinas Kancleris (Semiconductor Physics Institute, Lithuania)

- **Advances in High Power Microwave Sources and Technologies, IEEE Press**
  (AFOSR/MURI)
  - Professor Edl Schamiloglu (co-editor)
  - Dr. Robert J. Barker (AFOSR, co-editor)

UNIVERSITY OF MICHIGAN
R.M. Gilgenbach (Project Director)
Y.Y. Lau (Co-Principal Investigator)

Tasks

- **MICROVAVE PULSE SHORTENING MECHANISMS AND MITIGATION**
  - Professor R.M. Gilgenbach (directs experimental research)
  - Reginald Jaynes (graduate Student)
  - William Cohen (graduate student)
  - Chris Peters (graduate student)

- **THEORY: MICROWAVE MULTIPACATOR OF WINDOWS**
  - Professor Y.Y. Lau (directs research)
  - Agust Valfells (graduate student)

MICROWAVE SCIENCES, INC. (MSI)
Dr. Jim Benford, Principal Investigator

Task

- **Pulse Shortening in HPM Generators**
- **Transition to Better HPM Source Surface and Vacuum Conditions**
- **Low-Closure-Rate Cathode Materials at High Electric Fields.**
- **Vircator Studies**

EXECUTIVE SUMMARIES

TEXAS TECH UNIVERSITY

The main emphasis during the final contract period was on breakdown of microwave windows. A theoretical understanding of this phenomenon was reached. It was shown that the basic processes are the same as for unipolar breakdown provided the microwave frequency is less than the "hopping" frequency of electrons along the dielectric surface. The results were documented in a journal paper and several conference proceeding papers.

i. "Microwave Magnetic Field Effects on High Power Microwave Window Breakdown, D. Hemmert, A. Neuber, J. Dickens, H. Krompholz, L.L. Hatfield, and M. Kristiansen, accepted for publication in IEEE Transaction on Plasma Science, 2000.
ii "High Power Microwave Window Breakdown under Vacuum and Atmospheric Conditions" D. Hemmert, A. Neuber, J. Dickens, H. Krompholz, L.L. Hatfield, and M. Kristiansen, SPIE's International Symposium on AeroSense, (Intense Microwave Pulsed VII), 24-28, April 2000, Orlando, FL
iii. "Dielectric/Gas Interface Breakdown Caused by High Power Microwaves", D. Hemmert, A. Neuber, H. Krompholz, L.L. Hatfield, and M. Kristiansen, 13th International Conference on High Power Particle Beams, June 2000.
ix. "High Power Microwave Interface Breakdown", A, Neuber, D. Hemmert, H. Krompholz, L.L. Hatfield, and M. Kristiansen, EUROEM 2000, Edinburgh, UK, June 2000.
v. "Pressure Dependence of High Power Microwave Solid Dielectric/Gas Breakdown, A, Neuber, D. Hemmert, H. Krompholz, L.L. Hatfield, and M. Kristiansen, 27th IEEE International Conference on Plasma Science, New Orleans LA, June 2000

UNIVERSITY OF NEW MEXICO

The University of New Mexico (UNM) completed its research program on compact sources of high-energy microwaves. During the final year of funding the UNM group accomplished the following tasks:

i. Accepted delivery on a DURIP-funded brazed ceramic insulator stack for its long pulse accelerator,
ii. Investigated long pulse BWO operation in the cross-excitation regime in greater detail and suggested its use for HPM effects studies,
iii. Demonstrated operation of a radial transit time oscillator (the Radial Acceletron) at AFRL,
iv. Initiated first experimental set-up for the Educational Reltron (DURIP matching funds-supported),
v. Demonstrated the use of the Gigawatt-level Smart Tube to characterize dispersive properties of a 1-D photonic crystal and measured superluminal wave propagation in regions of anomalous dispersion, and
vi. tested resistive sensors with very sharp rise times for in situ measurement of large HPM power densities (collaboration with Semiconductor Physics Institute, Vilnius, Lithuania, EOARD-supported).

In addition, intense effort was expended on the preparation of a collaborative book describing the entire MURI HPM program. At this point version 2.0 of this book has been completed and the revised publication date by IEEE Press is January 2001.

UNIVERSITY OF MICHIGAN

University of Michigan research during the final project period focused on two areas that are crucial to the generation of long-pulse, high power microwaves: 1) experimental investigation and MITIGATION of microwave pulse shortening in HPM tubes, and 2) theoretical explorations of multipactor on a single surface of microwave windows.

UM experimental research successfully demonstrated that the average microwave pulse-length and time-integrated microwave energy of sources can be increased by plasma cleaning of the microwave structure. The coaxial gyrotron was cleaned by a nitrogen plasma generated by 50 watts from a 13.56 MHz radio frequency generator. Depending upon the initial conditions and the cleaning technique, increases in integrated microwave energy from 15% up to 245% were achieved over the baseline, dirty microwave tube. Spectroscopic measurements were also made of the effects of RF plasma cleaning upon hydrogen plasma line emission.

UM's theory of multipactor on a dielectric has been greatly extended to include the effect of an oblique RF electric field. It was found that if the RF electric field is at an angle more than 5 -10 degrees from the tangent to the dielectric surface, the susceptibility is greatly reduced. We also found that the inclusion of RF magnetic field does not change the saturation level or saturation mechanism of multipactor, but may make the dielectric much more vulnerable to multipactor over a much wider range of power levels. These works appear in Valfells, Ang, Lau, and Gilgenbach, "Effects of an External Magnetic Field and of an Oblique Electric Field on Multipactor Discharge on a Dielectric," Physics of Plasmas 7, 750 (2000).

In the latter part of the summer of 1999, U. of Michigan graduate student, Agust Valfells, spent over a week at UC Berkeley (host: Dr. John Verboncoeur) to collaborate on simulations of multipactor on a dielectric. That collaboration added considerable insight on the effect of space charge shielding, first alluded to by Andreas Neuber of Texas Tech. Subsequently, Valfells constructed a simple, consistent, solution that gives the energy distribution of the multipactoring electrons when they strike the dielectric at the steady state. He found that multipactor delivers about 3 percent of the RF energy to the dielectric (up from half to one percent from earlier estimates). These new findings were quickly written up as a joint paper between UM and UCB. It is scheduled to appear in the June, 2000 issue of IEEE Transactions on Plasma Science (Special Issue on HPM).

Y. Y. Lau collaborated with John Luginsland of AFRL to develop a theory of beam loading that explained (1) why the injection-locked RKO at AFRL ceases to operate when the beam current becomes too high, and (2) why the MILO functions better with a plasma at the downstream position.

MICROWAVE SCIENCES, INC.

The MSI work is concentrated on understanding and overcoming pulse shortening by gaining a more fundamental understanding of the physics of this phenomena and by assisting the Universities in the transition to better HPM source surface and vacuum conditions. MSI is also pursuing microwave pulse extension by development of low-closure-rate cathode materials. Principal recent activities:

i. Continued exploration of the implications of the general model for pulse shortening derived last year. Completed work as 'Chapter Master' for the Pulse Shortening chapter in the fourth-coming MURI-based book. Kept the subject of pulse shortening highly visible in the community by panels, talks and papers.

ii. Discussed cathode plasma simulation and carbon fiber cathodes, in collaboration with UCB and AFRL Albuquerque personnel. We have used this as a means of understanding pulse shortening and improving cathodes.

iii. Explored a new area of interest to the Air Force, microwave-driven propulsion. The primary interest at present is from NASA. Therefore Marshall Space Flight Center provided the initial funding for the modeling and experiments we have conducted. We have kept the AFRL informed of our work and may conduct an experiment at Kirtland in the future using their more powerful sources. I attended several NASA workshops and will soon present papers [described below] at EuroEM 2000 and Eleventh Advanced Space Propulsion Research Workshop (APC2000).

RESEARCH AREAS AND OBJECTIVES

Each university in the consortium has its own specific research areas and goals, with Microwave sciences, Inc. (as well as the other industrial partners listed with the two other consortia) serving mainly in an advisory and support role. The overall program is basic (6.1) and is aimed at developing knowledge, understanding, and techniques that will be useful for developing improved HPM sources in the future. Obvious examples are achieving an understanding of pulse shortening phenomenon and developing a control strategy for "smart tubes" and establishing design criteria for Ultra Wide Band system design.

Research emphasis within the consortium includes the following topics and goals:

TEXAS TECH UNIVERSITY

Microwave Vacuum and Window Breakdown

(Summary of work completed in the year 1999-2000)

Dielectric-gas interface breakdown was measured for a variety of gasses. The travelling wave resonant ring (TWRR) was modified to produce a pressurized test region capable of pressures up to 10^3 Torr. Dielectric surface breakdown strengths were then studied from 10^3 Torr down to 10^{-4} Torr for air, SF_6, and argon, and compared to our previous results for breakdown in vacuum. Additionally, volume gas breakdown was studied within the test region and compared to the dielectric interface breakdown strengths. Finally, a literature search produced data for comparison to the acquired results. At high pressures, 0.1 Torr to 10^3 Torr, dielectric-gas surface breakdown fields and volume breakdown fields as a function of pressure displayed a similar relation, with slightly lower breakdown fields for dielectric-gas interfaces due to the field enhancement caused by the dielectric. Drastic differences appear when comparing volume and dielectric breakdown at lower pressures, because then, free electrons play a dominant role, as exhibited by a significant increase in the x-ray signal. Dielectric-gas breakdown field strengths for air, SF_6, and argon are similar at low pressures, but diverge at high pressures. This is consistent with free electrons dominating breakdown at low pressures, while gas ionization processes dominate at high pressures. SF_6 exhibited the highest breakdown field strength at high pressure (atmosphere) and argon exhibited the lowest. The volume breakdown results were compared to results from the literature and showed a similar trend for breakdown field strengths as a function of pressure. Absolute breakdown levels were not comparable except in one case. This difference was associated with the short rise- time, linearly rising field in our TWRR compared to the constant field over a long time associated with the data in the literature. Our data represents the lower limit of breakdown fields on alumina interfaces and can be used as a guideline for window design. These results have been presented at SPIE Aerosense 2000 in Orlando, FL, and will be presented at ICOPS 2000 in New Orleans, LA, and BEAMS 2000 in Nagaoka, JP.

Ultra Wide Band Microwave Generation

No work has been done on this project since September 1999 but will be continued under the New World Vistas program.

Vircator

The alternate vircator geometry research was terminated on 31 July 1999. In the beginning of the year 2000, the work was re-established with alternate funding. The new research effort was aimed at increasing the pulse forming line by an additional 4.3 meters for a total of 6.7 meters to obtain approximately a 70 ns flat top pulse. To accommodate the increased length, the oil filter system was modified. In addition to increasing the length of the transformer line a new voltage probe was designed, built, and tested to eliminate the need for computer manipulation of the acquired waveform. New pre-pulse resistors were made and installed. The vacuum system was re-worked and the current and voltage probes were calibrated with commercial probes for accuracy. Finally, timing lines were established for the diagnostics. Cooperation work on B-D PIC simulations was conducted with W. Jiang, Nagaoka University of Technology, Japan.

UNIVERSITY OF NEW MEXICO

Hybrid Hard Tube BWO

Goal: To demonstrate pulse lengthening in a long pulse BWO by providing a higher quality vacuum and surface environment inside the HPM source.

We have received (DURIP'97 funding) a brazed ceramic insulator stack designed and built by Titan/PSI. Modifications are being made based on results from Michigan stack. Awaiting final recommendations from Titan/PSI.

Long Pulse Intense Beam BWO: Cross-Excitation Instability

Goal: To better understand BWO operation in the cross-excitation regime.

We have invoked time-frequency analysis to better understand the dozens of shots we have in our database for BWO operation in the cross-excitation regime. We are suggesting that better understanding and control of this regime can lead to potentially useful HPM effects studies.

Radial Acceletron Transit Time Oscillator

Goal: To demonstrate the operation of a novel HPM source designed entirely using PIC simulations.

Microwave generation has been demonstrated and preliminary indications are that the results are in agreement with PIC studies. The experiment is very sensitive to the Q of the system and this sensitivity has been borne out in numerical studies. The dissertation is being finalized and the student will graduate at the end of summer.

Educational Reltron HPM Source

Goal: To develop a compact HPM source for graduate student education.
This source was installed last year in our laboratory. The power supply was damaged and we are awaiting a replacement from Titan/PSI. Delays in our ceramic insulator stack installation has led to delays in delivery of the source. A M.S. student is presently working on the source, setting up diagnostics.

HPM Characterization of Photonic Crystals

Goal: To demonstrate how a narrowband HPM source operating in the TE_{11} mode is an ideal generator of a wavepacket for studying fundamental aspects of electromagnetic wave propagation in regions of anomalous dispersion.

We have demonstrated the use of the Smart Tube frequency agile HPM source to study electromagnetic wave propagation through the stop band of a 1-D photonic crystal. Although the signal is evancescent, the waveform is preserved and superluminal group and energy velocities have been documented. AFRL lent us two SCD 5000 scopes to measure the group delay of the electromagnetic waves.

Resistive Sensor for HPM Measurement

Goal: To develop resistive sensors to directly measure power densities generated by HPM sources without resorting to large attenuations.

In collaboration with our Lithuanian colleagues, we have developed X-band resistive sensors based on thermal effects of electrons drifting in silicon under the influence of large electric fields. These sensors were built in Lithuania and were customized to provide fast risetimes to measure short pulse HPM signals. The sensors were investigated at UNM and further improvements are being made. These sensors offer the advantage of measuring HPM signals directly in waveguide with resorting to large signal attenuation and calibration errors associated with that technique.

Advances in High Power Microwave Sources and Technologies, IEEE Press

Goal: To submit to IEEE Press a final edited book summarizing the entire FY '94 HPM MURI program across all three consortia.

The second draft of the book was delivered May 27. The complete book will be delivered before the end of July 2000. The book will appear early 2001.

UNIVERSITY OF MICHIGAN

Microwave Pulse Shortening and Mitigation

1. Identify the physical mechanisms of high power microwave pulse shortening

2. Develop a technique for mitigation of microwave pulse shortening by RF plasma cleaning

3. Understand the role of multipactor in causing pulse shortening, focussing on the vacuum-dielectric interface.

4. Understand and model the effects of beam loading on HPM sources.

Microwaves Sciences, Inc.

Pulse Shortening

Microwave Sciences Inc. (MSI) has concentrated on understanding and overcoming this key problem by gaining a more fundamental understanding of the physics of pulse shortening. In this work we have:

1. Continued to explore the implications of the general model for pulse shortening derived last year and compared to data from several varieties of sources, with good agreement.

2. Served as 'Chapter Master' for the Pulse Shortening chapter in the fourth-coming book "*Advances in High Power Microwave Source Research and Technologies*".

3. Worked to keep the subject of pulse shortening highly visible in the community by panels, talks and papers.

Transition to Better HPM Source Surface and Vacuum Conditions

Communicated 'lessons learned' about surface conditioning, bakeout, and material selection in detail by visiting the Universities in the MURI program, especially Michigan and New Mexico, which are making serious efforts to improve surface and vacuum conditions.

Low-Closure-Rate Cathode Materials at High Electric Fields.

Assisted the cathode work at PL, which started in 1998. Located an industry source of Carbon-Carbon fiber fabrication that solves the problem of making a large-area low outgassing, low closure-rate cathode compatible with high temperature. This has recently resulted in better cathode performance. AFRL is now ordering and using much larger

area cathodes made of the carbon-fiber material ('C-C Microtruss' made by Energy Science Laboratories Inc., San Diego).

Vircator Studies

Continued a low level of work toward a virtode experiment, which is now planned to be done in 2000 at TTU.

SUMMARY OF COLLABORATIVE ACTIVITIES/AWARDS/THESES
1 Sept. 1999 – 14 April 2000

TEXAS TECH UNIVERSITY

With AFOSR:

M. Kristiansen discussed on-going research with Dr. R. Barker in Washington, DC

Honors/Awards:

M. Kristiansen

Presented the IEEE Millenium Medal at the ICOPS meeting in New Orleans, La in June 2000.

Invited paper and session chair at Beams .

Invited paper at ICOPS with Jane Lehr of AFRL.

Coop with University of Nagaoka on vircator simulations.

UNIVERSITY OF NEW MEXICO

Within MURI Central:

Worked with Michigan on understanding performance of brazed ceramic insulator stack. Worked with Texas Tech on using fast framing camera on UNM BWO for light emission studies associated with pulse shortening.

Worked with Microwave Sciences on studying use of HPM for light sails.

Other Consortia:

Worked with everyone on the IEEE Press book.

With AFRL:

Radial Acceletron Research and use of HPM source for fundamental studies of electro-magnetic wave propagation in regions of anomalous dispersion.

With Industry:

Titan/PSI in brazed ceramic insulator stack and Educational Reltron.

International:

Institute of High Current Electronics, Tomsk, Russia: Bragg Reflectors (Dr. Sergei Korovin)

Institute of Applied Physics, Nizhny Novgorod, Russia: BWO Theory with low B-field (Drs. Michael Petelin and Mikhail Fuchs)

Tomsk Polytechnic Institute, Tomsk, Russia: Hybrid Antenna/Amplifier Research Semiconductor Physics Institute, Vilnius, Lithuania: HPM Resistive Sensors.

Honors/Awards:

Professor Schamiloglu:
Appointment as University Regents' Lecturer Continued Promoted to Professor of Electrical and Computer Engineering Awarded 3-year Endowed Chair as "Gardner-Zemke" Professor.

Professor Abdallah:
Promoted to Professor of Electrical and Computer Engineering Received Lawton-Ellis Award for outstanding EECE professor Received IEEE Millenium Medal (from IEEE local chapter).

Mohammad Mojahedi:
Received Popejoy Award for best doctoral thesis at UNM in 1999-2000 academic year

Kelly Hahn:
Received King Fellowship as outstanding graduate student.

MURI-Related Service:

Professor Schamiloglu:
Associate Editor, IEEE Transactions on Plasma Science
Elected to IEEE Nuclear and Plasma Science AdCom representing Pulsed Power Science and Technology Standing Committee
Elected to IEEE Nuclear and Plasma Science/Plasma Science and Applications Excom
Session Chair at EUROEM on HPM.

UNIVERSITY OF MICHIGAN

UM with UC Berkeley, in the simulation and analysis of multipactor, focussing on the space charge shielding effects. This resulted in a joint publication in archival journal [Valfells, Lau, and Verboncoeur, IEEE Trans. Plasma Sci. (6/2000 issue)].

UM with Lisa Laurent of UC Davis and Andreas Neuber of Texas Tech: Lau analyzed the multipactor experiments in the SLAC klystron, as reported in the Chapter on RF Breakdown in the forthcoming IEEE HPM Book (Eds. Barker and Schamiloglu).

UM with John Luginsland and AFRL: Lau modeled beam loading effects on RKO and MILO. These works were presented at SPIE (Orlando) and ICOPS (New Orleans).

Tom Spencer from AFRL served on the UM doctoral committee of Reginald Jaynes. He visited Michigan for the Ph.D. defense and assisted UM in high power microwave experimental data acquisition.

Honors/Awards:

Ron Gilgenbach received the annual award from the department of Nuclear Engineering and Radiological Sciences.

MICROWAVE SCIENCES

Visits

To Phillips Laboratory for discussions on MILO, cathodes and microwaves for space propulsion with Mike Haworth, and Kyle Hendricks, October 2-3, 1999 and March 20-23, 2000.

To UNM, October 2, 1999 and March 20, 2000.

Other Collaborations

Discussions of TTU vircator experiment data and future virtode plans, winter 1999-2000.

Discussions of cathode development and simulation with John Verbonceour and Ned Birdsall, winter 1999-2000.

SUMMARY OF PUBLISHING ACTIVITIES

September 1, 1999 through April 14, 2000

TEXAS TECH UNIVERSITY

Journal Papers

1. "The Role of Outgassing in surface Flashover under Vacuum", A. Neuber, J. Dickens, H. Krompholz, and M. Kristiansen, accepted for publication in special issue on Pulsed Power in IEEE Transaction on Plasma Science, 2000.

2. "Microwave Magnetic Field Effects on High Power Microwave Window Breakdown", D. Hemmert, A. Neuber, J. Dickens, H. Krompholz, L.L. Hatfield and M. Kristiansen, accepted for publication in Special Issue on High Power Microwaves in IEEE Transactions on Plasma Science, 2000.

3. "High Power Microwave Generation by a Coaxial Virtual Cathode Oscillator", W. Jiang, K. Woolverton, J. Dickens and M. Kristiansen, IEEE Transactions on Plasma Science, 27 5, 1538-1542, October 1999.

4. "Efficiency Enhancement of a Coaxial Virtual Cathode Oscillator", W. Jiang, J. Dickens and M. Kristiansen, Trans. Plasma Sci., 27 5, 1543-1547, October 1999.

Conference Proceedings

5. "High Power Microwave Window Breakdown under Vacuum and Atmospheric Conditions", D. Hemmert, A. Neuber, J. Dickens, H. Krompholz, L.L. Hatfield and M. Kristiansen, SPIE's International Symposium on AeroSense, (Intense Microwave Pulses VII", 24-28, April 2000, Orlando, FL

6. "Dielectric/Gas Interface Breakdown Caused by High Power Microwaves", D. Hemmert, A. Neuber, H. Krompholz, L.L. Hatfield and M. Kristiansen, 13th International Conference on High-Power Particle Beams, June 2000, Nagaoka, Japan (invited).

7. "High-Power Microwave Generation by a Coaxial Vircator", W. Jiang (Nagaoka University of Technology), Jim Dickens and M. Kristiansen, 13th International Conference on High-Power Particle Beams June 2000, Nagaoka, Japan.

8. "3-D PIC Simulation of a Coaxial Vircator", W. Jiang, (Nagaoka University of Technology), Jim Dickens and M. Kristiansen, 13th International Conference on High-Power Particle Beams June 2000, Nagaoka, Japan.

Conference Abstracts/Presentations

9. "High Power Microwave Interface Breakdown", A. Neuber, D. Hemmert, H. Krompholz, L.L. Hatfield and M. Kristiansen, EUROEM 2000, Edinburgh, UK, June 2000.

10. "Pressure Dependence of High Power Microwave Solid Dielectric/Gas Interface Breakdown", A. Neuber, D. Hemmert, H. Krompholz, L.L. Hatfield and M. Kristiansen, 27th IEEE International Conference on Plasma Science, New Orleans, LA, June 2000.

UNIVERSITY OF NEW MEXICO

Books

1. R.J. Barker and E. Schamiloglu, Advances in High Power Microwave Sources and Technologies (IEEE Press, New Jersey, 2001).

2. J. Benford, J. Swegle, and E. Schamiloglu, High Power Microwaves, 2nd Ed. (Institute of Physics Publishing, Bristol, UK, 2002).

Journal Publications

1. "Frequency Domain Detection of Superluminal Group Velocity in a Distributed Bragg Reflector," M. Mojahedi, E. Schamiloglu, K. Agi, and K.J. Malloy, IEEE J. Quantum Electron., vol. 36, 418-424, 2000.

2. "Iterative Learning Control Applications to High Power Microwave Tubes," V.S. Soualian, G.T. Park, C.T. Abdallah, and E. Schamiloglu, accepted (with revisions) IEEE Trans. Control Sys. Tech. (to appear 2000/2001).

3. "Electron Emission from Thin-film Ferroelectric Cathodes," F. Liu and C.B. Fleddermann, Appl. Phys. Lett., vol. 76, 1618-1620, 2000.

4. "Studies of Relativistic Backward Wave Oscillator Operation in the Cross-Excitation Regime," F. Hegeler, M. Partridge, E. Schamiloglu, and C.T. Abdallah, accepted and to appear in IEEE Trans. Plasma Sci., Special Issue on High Power Microwave Generation, June, 2000.

5. "Time Domain Detection of Superluminal Group Velocity Using Single Microwave Pulses," M. Mojahedi, E. Schamiloglu, F. Hegeler, G.T. Park, K. Agi, and K.J. Malloy, in preparation for submittal to Phys. Rev. E., 2000. (No abstract available at this time.)

Conference Proceedings

6. "Detection of Superluminal (but Causal) Group Velocity in One-Dimensional Photonic Crystals using a High Power Microwave Source" E. Schamiloglu, M. Mojahedi, F. Hegeler, G.T. Park, K. Agi, and K.J. Malloy, (Plenary Session Paper), Digest 24th International Conference on Infrared and Millimeter Waves, Monterey, CA, September 1999, p. P.Tu.2-3.

7. "X-band Resistive Sensors for Short High-Power Microwave Pulse Monitoring," M. Dagys, Z. Kancleris, R. Simniskis, E. Schamiloglu, and F.J. Agee, Proc. 29th European Microwave Conference, Munich, Germany, p. 65-68, October 1999.

8. "Experimental Studies of the Cross-Excitation Instability in a Relativistic Backward Wave Oscillator," E. Schamiloglu, F. Hegeler, M. Partridge, C.T. Abdallah, and N. Islam, submitted to Intense Microwave Pulses VII, SPIE AeroSense 2000, Orland, FL, April 2000 (in press).

Conference Abstracts/Presentations:

9. "Use of a High Power Microwave Source to Detect Superluminal Group Velocities," M. Mojahedi, K. Malloy, E. Schamiloglu, F. Hegeler, and G. Park, Bull. Am. Phys. Soc., vol. 44, 253, 1999.

10. "Analysis of the Cross-Excitation Instability in Relativistic Backward Wave Oscillator," E. Schamiloglu, F. Hegeler, C. Abdallah, and M. Partridge, Bull. Am. Phys. Soc., vol. 44, 296, 1999.

11. "Overview of Intense Beam-Driven Relativistic Backward Wave Oscillators and their Use in High Power Microwave Effects Studies," E. Schamiloglu, F. Hegeler, C.T. Abdallah, K. Hahn, and S. Choi, submitted to the IEEE International Conference on Plasma Science, New Orleans, LA, June 2000.

12. "Envelope Power Sensors for HPM Measurement," M. Dagys, Z. Kancleris, R. Simniskis, E. Schamiloglu, and F.J. Agee, submitted to EUROEM 2000, Edinburgh, Scotland May 30 - June 2, 2000.

13. "An Overview of Recent Advances in Intense Beam-Driven Relativistic Backward Wave Oscillators and their Use in High Power Microwave Effects Studies," E. Schamiloglu, F. Hegeler, C.T. Abdallah, and C.G. Christodoulou, submitted to EUROEM 2000, Edinburgh, Scotland May 30 - June 2, 2000.

Ph.D. Dissertations:

M. Mojahedi, "Superluminal Group Velocities and Structural Dispersion," (May 2000) (co-supported with ARO).

R.L. Wright, "A Radial Transit Time Oscillator," (August 2000).

M.S. Thesis:

Michael Partridge, "Reduced Complexity Feedback Equalizers for Wideband Channels," (August 2000).

UNIVERSITY OF MICHIGAN

Journal Papers

1. "Long Pulse, High Power, Large Orbit, Coaxial Gyrotron Oscillator Experiments", R.L. Jaynes, R.M. Gilgenbach, C.W. Peters, W.E. Cohen, M.R. Lopez, Y.Y. Lau, W.J. Williams, and Thomas A. Spencer, in press for IEEE Transactions of Plasma Science, 2000.

2. "Effects of an External Magnetic Field, and of Oblique Radio-Frequency Electric Fields on Multipactor Discharge on a Dielectric", A. Valfells, L.K. Ang, Y.Y. Lau, and R.M. Gilgenbach, Physics of Plasmas, 7 750 (Feb. 2000).

Conference Papers

3. "Resonant Absorption of a Short-Pulse Laser in a Doped Dielectric", L.K. Ang, Y.Y. Lau, R.M. Gilgenbach, B. Qi; Bulletin of the American Physical Society, vol. 44, No. 7, Nov. 1999 ; Presented at APS Division of Plasma Physics Annual Meeting Nov. 15-19, 1999.

4. "Plasma Processing and Optical Emission Spectroscopy in High Power Microwave Pulse Shortening Experiments" W.E. Cohen, R.M. Gilgenbach, R.L. Jaynes, C.W. Peters, M.R. Lopez, J.I. Rintamaki, Y.Y. Lau , T.A. Spencer; Bulletin of the American Physical Society vol. 44, No. 7, Nov. 1999; presented at APS Division of Plasma Physics Annual Meeting Nov. 15-19, 1999.

5. "Comparison of Slotted and Unslotted Multi-MW Large Orbit, Axis-Encircling, Coaxial Gyrotron Oscillators ", R.L. Jaynes, R.M. Gilgenbach, C.W. Peters, W.E. Cohen, M.R. Lopez, J.M. Hochman, Y.Y. Lau, T.A. Spencer; Bulletin of the American Physical Society vol. 44, No. 7, Nov. 1999; presented at APS Division of Plasma Physics Annual Meeting; Nov. 15-19, 1999.

6. "Time-Frequency Analysis of High Power Microwaves Using Discrete Prolate Spherical Sequences", C.W. Peters, R.M. Gilgenbach, W.J. Williams, Y.Y. Lau, R.L. Jaynes, W.E. Cohen, M.R. Lopez, T.A. Spencer; Bulletin of the American Physical Society vol. 44, No. 7, Nov. 1999; presented at APS Division of Plasma Physics Annual Meeting Nov. 15-19, 1999.

7. "Effects of Magnetic Fields, and of Oblique RF Electric Fields on Susceptibility to Multipactor Discharge on a Dielectric", A. Valfells, L.K. Ang, Y.Y. Lau, R.M. Gilgenbach; Bulletin of the American Physical Society vol. 44, No. 7, Nov. 1999; presented at APS Division of Plasma Physics Annual Meeting Nov. 15-19, 1999.

8. "Multipactor Discharge and RF Window Failure", Bulletin of the American Physical Society, Rex Anderson, A. Valfells, L.K. Ang, Y.Y. Lau, R.M. Gilgenbach, J. Verboncoeur, A. Neuber, H. Krompholz; vol. 44, No. 7, Nov. 1999; presented at APS Division of Plasma Physics Annual Meeting Nov. 15-19, 1999.

Ph.D. Dissertations:

Reginald Jaynes, M.S. and Ph.D., Thesis: "Generation of High Power Microwaves in a Large Orbit Coaxial Gyrotron, defended on January 17, 2000 (employed by Raytheon).

William Cohen, M.S. and Ph.D., Thesis: "Optical Spectroscopy and Effects of Plasma in High Power Microwave Gyrotron Experiments", Defended on May 10, 2000, (employed by GE Lighting).

Agust Valfells, M.S. and Ph.D., "Multipactor Discharge: Frequency Response, Suppression, and Relation to Window Breakdown", Defended on April 10, 2000.

M.S. Theses:

Chris Peters, M.S. (4/30/98), "Application of Time-Frequency Analysis to High Power Microwave Source Analysis", Ph.D. expected 2000-01,

MICROWAVE SCIENCES, INC. PUBLISHING ACTIVITIES

Conference Papers

1 "Microwave Beam-driven Propulsion Experiments for High-Speed Space Exploration", James Benford, Henry Harris, Gregory Benford, and Timothy Knowles EuroEM, May 30-June 2, 2000, Edinburgh, Scotland [Talk].

2. Microwave Beam-Driven Sail Flight Experiments", James Benford, Henry Harris, Gregory Benford, Timothy Knowles, Keith Goodfellow and Raul Perez, Eleventh Advanced Space Propulsion Research Workshop (APC2000), Pasadena, CA, May 29-June 2, 2000 [Invited Talk, to be given by Gregory Benford].

APPENDIX

The following appendix lists the abstracts for all journal and conference papers and also lists the recently submitted conference abstracts.

Accepted for Publication is special issue on Pulsed Power in IEEE Transaction on Plasma Science, 2000

THE ROLE OF OUTGASSING IN SURFACE FLASHOVER UNDER VACUUM

A. Neuber, *Member, IEEE*, M. Butcher, H. Krompholz, *Senior Member, IEEE*, L.L. Hatfield, *Member, IEEE*, M. Kristiansen, *Life Fellow, IEEE*

Abstract— **Results of high-speed electrical and optical diagnostics are used as a basis to discuss a new surface flashover model. Outgassing, caused by electron stimulated desorption, is found to play a crucial role in the temporal flashover development. Dielectric unipolar surface flashover under vacuum is experimentally characterized by a three-phase development, that covers a current range from 10^{-4} A to 100 A. Phase one comprises a fast (several nanoseconds) build-up of a saturated secondary electron avalanche reaching current levels of 10 to 100 mA. Phase two is associated with a slow current amplification reaching currents in the Ampere level within typically 100 nanoseconds. The final phase is characterized by a fast current rise up to the impedance-limited current on the order of 100 A. The development during phase two and three is described by a zero-dimensional model, where electron-induced outgassing leads to a Townsend-like gas discharge above the surface. This is supported by time-resolved spectroscopy that reveals the existence of excited atomic Hydrogen and ionic Carbon before the final phase. The feedback mechanism towards a self-sustained discharge is due to space charge leading to an enhanced field emission from the cathode. *A priori* unknown model parameters, such as outgassing rate and gas density build-up above the surface, are determined by fitting calculated results to experimental data. The significance of outgassing is also discussed with a view to microwave surface flashover.**

Index Terms— **Flashover, Surface Flashover, High Power Microwave, Outgassing, Electric Breakdown, Optical Spectroscopy, Pulse Measurements**

Accepted for publication in Special Issue on High Power Microwave in IEEE Transactions on Plasma Science

Microwave Magnetic Field Effects on High Power Microwave Window Breakdown

D. Hemmert, A. Neuber, J. Dickens, H. Krompholz, L. L. Hatfield, M. Kristiansen

Departments of Electrical Engineering and Physics

Texas Tech University, Lubbock, TX 79409-3102

Abstract–Microwave window breakdown in vacuum is investigated for an idealized geometry, where a dielectric slab is located in the center of a rectangular waveguide with its normal parallel to the microwave direction of propagation. An S-band resonant ring with a frequency of 2.85 GHz and a power of 60 MW is used. With field enhancement tips at the edges of the dielectric slab, the threshold power for breakdown is observed to be dependent on the direction of the microwaves, i.e. it is approximately 20 % higher for the downstream side of the slab than for the upstream side. Simple trajectory calculations of secondary electrons in an rf field show a significant forward motion of electrons parallel to the direction of microwave propagation. Electrons participating in a saturated secondary avalanche on the upstream side are driven into the surface, electrons on the downstream side are driven off the surface, due to the influence of the microwave magnetic field. In agreement with the standard model of dielectric surface flashover for dc conditions (saturated avalanche and electron induced outgassing), the corresponding change in the surface charge density is expected to be proportional to the applied breakdown threshold electric field parallel to the surface.

Index terms-- microwave devices, dielectric breakdown, electron emission, magnetic field effects, magnetic insulation

This work was solely funded by the High Energy Microwave Device MURI program funded by the Director of Defense Research & Engineering (DDR&E) and managed by the Air Force Office of Scientific Research (AFOSR).

1538 IEEE TRANSACTIONS ON PLASMA SCIENCE, VOL. 27, NO. 5, OCTOBER 1999

High Power Microwave Generation by a Coaxial Virtual Cathode Oscillator

Weihua Jiang, Kevin Woolverton, James Dickens, *Member, IEEE*, and Magne Kristiansen, *Life Fellow, IEEE*

***Abstract*—A new type of virtual cathode oscillator, the coaxial vircator, was studied analytically and experimentally. A one-dimensional analytical model was used to describe the steady-state behavior of the electron beam and the virtual cathode, from which the diode current, the space-charge limited current, the virtual cathode position, and the estimated oscillation frequency were obtained. The experiments were carried out with typical electron-beam parameters of 500 kV, 40 kA, and 30 ns, where pulsed microwaves of 400 MW in peak power and 2 GHz in frequency have been obtained. The energy efficiency from the electron beam to microwaves was ~2%. This efficiency is expected to be improved by increasing the microwave field strength around the vircator.**

***Index Terms*—High-power microwaves, microwave devices, microwave measurements, pulsed power systems, relativistic electron beams.**

Technical Notes

Efficiency Enhancement of a Coaxial Virtual Cathode Oscillator

Weihua Jiang, James Dickens, and Magne Kristiansen

Abstract—The microwave field intensity around the virtual cathode oscillator was enhanced by using a microwave reflector in the output waveguide. The experimental results show that the microwave output power strongly depends on the position and geometry of the microwave reflector. The maximum microwave efficiency obtained was twice as large as that without field enhancement by the microwave reflector.

Index Terms— Efficiency enhancement, electron beam, high power microwaves, microwave reflector.

SPIE International Symposium on AeroSense, "Intense Microwave Pulses VII",
24-28 April 2000, Orlando, FL

High power microwave window breakdown under vacuum and atmospheric conditions

David Hemmert, Andreas A. Neuber, James C. Dickens,
Hermann Krompholz, Lynn L. Hatfield, and Magne Kristiansen
Pulsed Power Laboratory
Departments of Electrical Engineering and Physics,
Texas Tech University, Lubbock, TX 79409-3102

ABSTRACT

Microwave window breakdown is investigated in vacuum and atmospheric conditions. An S-band resonant ring with a frequency of 2.85 GHz and a power of 80 MW with a 4 MW magnetron as a source is used. Window breakdown on the vacuum side is simulated using a dielectric slab partially filling an evacuated waveguide. Various high-speed diagnostic methods yield a complete picture on the breakdown phenomenology, with far reaching similarities to dc surface flashover. During the initiation phase, free electrons are present, which can be influenced by magnetic fields, followed by a saturated secondary electron avalanche with electron-induced outgassing. Final breakdown occurs in the desorbed gas layer above the surface. In order to simulate window breakdown on the gas-side, a segment of the resonant ring separated by two windows was filled with gas at variable pressure, and breakdown was initiated by field-enhancement tips on one of the gas-side surfaces. Threshold power densities for breakdown are measured, and first results on the phenomenology of this gas breakdown are compared with the processes of flashover in vacuum.

This work was solely funded by the High Energy Microwave Device MURI program funded by the Director of Defense Research & Engineering (DDR&E) and managed by the Air Force Office of Scientific Research (AFOSR).

Beams 2000 abstract, Topic D2: High Power Microwaves, Preference: oral, 5/4/00

DIELECTRIC/GAS INTERFACE BREAKDOWN CAUSED BY HIGH POWER MICROWAVES

D. Hemmert, A. Neuber, H. Krompholz, L.L Hatfield, and M. Kristiansen

Departments of Electrical Engineering and Physics, Pulsed Power Laboratory
Texas Tech University, Lubbock, TX 79409-3102

Physical mechanisms leading to microwave breakdown on dielectric/gas interfaces are investigated for power levels on the order of 10 MW/cm^2 at 2.85 GHz and gas pressures in the range of 10^{-4} torr to 10^3 torr. The investigation is focused on an alumina/air interface; other gases are considered for reference purposes. A 4 MW magnetron with 3.5 μs pulse width is coupled to an S-band traveling wave resonator with a pressure adjustable test region. The interface geometry comprises a thin dielectric alumina slab in the waveguide; the slab being oriented normal to the direction of wave propagation and in contact with two field enhancement tips placed in the middle of each waveguide broad wall. This ensures an almost purely tangential field at the interface surface and a localized breakdown.
The pre-breakdown phase and the breakdown are monitored by recording the traveling and reflected power, and the spatially integrated luminosity. Electric field probes in the vicinity of the interface are included as well to get information about the local field. Furthermore, the light emission was observed with an image intensifier capable of a minimum gate time of 2.5 ns, in temporal correlation to the other phenomena, or with a framing camera having a 20 ns gate time and 100 ns separation between pictures. The pressure dependent breakdown characteristics, such as appearance, breakdown field, and temporal behavior of electric signals, are compared to our dielectric/vacuum interface breakdown and volume breakdown results, all measured utilizing the same basic setup.

This work was solely funded by the High Energy Microwave Device MURI program funded by the Director of Defense Research & Engineering (DDR&E) and managed by the Air Force Office of Scientific Research (AFOSR).

HIGH-POWER MICROWAVE GENERATION BY A COAXIAL VIRCATOR

W. Jiang
Extreme Energy Density Research Institute, Nagaoka University of Technology, Nagaoka, Niigata 940-2188, Japan

J. Dickens and M. Kristiansen
Pulsed Power Laboratory, Dept. of Electrical and Computer Engineering Texas Tech University, Lubbock, TX 79409-3102, USA

A coaxial-type virtual cathode oscillator (vircator) was tested in the Pulsed Power Laboratory at Texas Tech University with electron beam parameters of 500 kV, 40 kA, and 30 ns. The major goal of this experiment was to understand the characteristics of the coaxial vircator and the effect of the feedback field on the microwave efficiency. The experimental results have given the output microwave power of ~ 400 MW, the microwave energy efficiency of ~ 2 %, the microwave frequency of ~ 2 GHz, and the microwave mode of TE_{11} in circular waveguide. By enhancing the field intensity around the vircator using a microwave reflector, the microwave output power was increased to ~ 900 MW giving microwave energy efficiency of ~ 5.5 %. This efficiency is calculated as peak microwave power divided by peak beam power, which does not occur at the same time. The instantaneous efficiency, using the beam power at the time of the peak microwave power is 20%.

This work was mostly funded by the High Energy Microwave Device MURI program funded by the Director of Defense Research and Engineering (DDR & E) and managed by the Air force Office of Scientific Research (AFOSR)

3-D PIC SIMULATION OF A COAXIAL VIRCATOR

W. Jiang
Extreme Energy Density Research Institute, Nagaoka University of Technology, Nagaoka, Niigata 940-2188, Japan

J. Dickens and M. Kristiansen
Pulsed Power Laboratory, Dept. of Electrical and Computer Engineering Texas Tech University, Lubbock, TX 79409-3102, USA

The experimental results of coaxial-type virtual cathode oscillator (vircator) have shown physically interesting characteristics of the coaxial vircator.[1)] However, the physical reason for some of the phenomena observed in the experiments were not very well understood. These phenomena includes: 1) the time delay between the peaks of the electron-beam power and the microwave power, 2) the nonsymmetric microwave mode (TE_{11}) formed in a symmetric system, and 3) the effect of the feedback field on electron beam bunching. In order to understand the physical issues related to these phenomena, a 3-dimensional particle-in-cell (PIC) simulation code was developed and used for studying the behavior of the coaxial vircator.

1) W. Jiang, J. Dickens and M. Kristiansen, in these proceedings.

This work was mostly funded by the High Energy Microwave Device MURI program funded by the Director of Defense Research and Engineering (DDR & E) and managed by the Air force Office of Scientific Research (AFOSR)

EUROEM 2000, Edinburgh, UK, June 2000

High Power Microwave Interface Breakdown

A. Neuber, D. Hemmert, H. Krompholz, L. L. Hatfield,
and M. Kristiansen*
Pulsed Power Laboratory
Departments of Electrical Engineering and Physics,
Texas Tech University, Lubbock, TX 79409-3102

The knowledge of the behavior of solid dielectric/gas interface breakdown caused by microwaves is crucial for developing new design methods for high power microwave windows. The physical mechanisms leading to breakdown for power levels on the order of 10 MW/cm^2 at 2.85 GHz and gas pressures varying from 10^{-4} to 10^3 Torr are investigated, with emphasis on alumina/air interfaces. The high power microwaves are generated with a 4 MW magnetron having a 3.5 _s pulse width in conjunction with an S-band traveling wave resonator, resulting in a traveling wave power of 100 MW. This power level is sufficient to cause breakdown across the interface located in the pressure adjustable test region. The interface geometry comprises a thin ceramic alumina slab placed in the waveguide center. An almost purely tangential field and a localized breakdown are assured by orienting the alumina slab normal to the direction of the wave propagation and by making contact with two field enhancement tips placed in the middle of each waveguide broad wall. We monitor the pre-breakdown phase and the breakdown by recording the traveling and reflected power, and the luminosity, spatially integrated with high temporal resolution or imaged with a framing camera. Additionally, we gain information about the local field by placing electric field probes in the vicinity of the interface. An image intensifier, capable of a minimum gate time of 2.5 ns and in temporal correlation to the other phenomena enables us to take single shot photographs of the light emission. We compare the pressure dependent breakdown characteristics, such as appearance, breakdown field, and temporal behavior of electric signals to our solid dielectric/vacuum interface breakdown and volume breakdown results, all measured utilizing the same basic setup.

This work was solely funded by the High Energy Microwave Device MURI program funded by the Director of Defense Research & Engineering (DDR&E) and managed by the Air Force Office of Scientific Research (AFOSR).

ICOPS 2000 abstract, Session 2.0: Microwave Generation and Microwave Plasma Interaction,
Preference: oral, 5/31/00

Pressure Dependence of High Power Microwave Solid Dielectric/Gas Interface Breakdown

A. Neuber, D. Hemmert, H. Krompholz, L. L. Hatfield, and M. Kristiansen
Pulsed Power Laboratory
Departments of Electrical Engineering and Physics,
Texas Tech University, Lubbock, TX 79409-3102

The knowledge of the behavior of solid dielectric/gas interface breakdown caused by microwaves is crucial for developing new design methods for high power microwave windows. We investigate the physical mechanisms leading to breakdown for power levels on the order of 10 MW/cm^2 at 2.85 GHz and gas pressures varying from 10^{-4} to 10^3 Torr. As an interface that is in widespread use, the focus was put on an alumina/air interface. Other gases are considered mainly for reference purposes. The high power microwave is generated with a 4 MW magnetron having a 3.5 μs pulse width in conjunction with an S-band traveling wave resonator. This approach provides a power gain of maximum 25, sufficient to cause breakdown across the interface located in the pressure adjustable test region. The interface geometry comprises a thin ceramic alumina slab placed in the waveguide center. We ensure an almost purely tangential field and a localized breakdown by orienting the alumina slab normal to the direction of the wave propagation and making contact with two field enhancement tips placed in the middle of each waveguide broad wall.

We monitor the pre-breakdown phase and the breakdown by recording the traveling and reflected power, and the luminosity, spatially integrated with high temporal resolution or imaged with a framing camera. Additionally, we gain information about the local field by placing electric field probes in the vicinity of the interface. An image intensifier, capable of a minimum gate time of 2.5 ns and in temporal correlation to the other phenomena enables us to take single shot photographs of the light emission with a better temporal and spatial resolution as compared to the framing camera. We compare the pressure dependent breakdown characteristics, such as appearance, breakdown field, and temporal behavior of electric signals to our solid dielectric/vacuum interface breakdown and volume breakdown results, all measured utilizing the same basic setup.

This work was solely funded by the High Energy Microwave Device MURI program funded by the Director of Defense Research & Engineering (DDR&E) and managed by the Air Force Office of Scientific Research (AFOSR).

418 IEEE JOURNAL OF QUANTUM ELECTRONICS. VOL. 36, NO. 4, APRIL 2000

Frequency-Domain Detection of Superluminal Group Velocity in a Distributed Bragg Reflector

Mohammad Mojahedi, Edl Schamiloglu, Kamil Agi, and Kevin J. Malloy

***Abstract*—Using a free-space configuration and a frequency-domain detection setup, group velocities of electromagnetic waves in a distributed Bragg reflector are investigated. Experimental data indicates that, near the regions of minimal transmission in our configuration, the group velocity is 2.1 times faster than the speed of light in vacuum. A transmission model based on diagonalization of the transfer matrix is used to compare the experimental data and the theoretical calculations, and good agreement between theory and experiment is obtained. An overview of the experimental uncertainties and their effects on the measured quantities is provided.**

***Index Terms*—Electromagnetic fields, electromagnetic propagation in a dispersive medium, mirrors, superluminal propagation, velocity measurement.**

Iterative Learning Control Applications to High Power Microwave Tubes

V. S. Soualian, G.T. Park, C.T. Abdallah, and E. Schamiloglu
EECE Department,
University of New Mexico,
Albuquerque, NM 87131, USA.

Abstract

In this paper, we present a "smart" high-peak power microwave tube, by implementing iterative learning control methodologies to control a repetitively-pulsed, high-power, backward wave oscillator. The learning control algorithm is used to drive the error between the actual output and its desired value to zero. The desired output may be a given power level, a given frequency, or a combination of both. The learning control methodology is then verified in simulation and in hardware.

APPLIED PHYSICS LETTERS VOLUME 76, NUMBER 12 20

Electron emission from thin-film ferroelectric cathodes

F. Liu and C. B. Fleddermann[a)]
Department of Electrical and Computer Engineering, University of New Mexico, Albuquerque, New Mexico 87131

(Received 2 November 1999; accepted for publication 18 January 2000)

Electron emission from thin-film (<1 μm thick) ferroelectric cathodes has been investigated. The cathodes were made using sol-gel deposition and standard microelectronic patterning techniques and were excited using either dc or pulsed bias. Repeatable emission current densities up to 10 μA/cm^2 were measured from 0.8-μm-thick lead-niobium-zirconium-titanate cathodes driven in the pulsed mode with switch voltages up to 22 V. Intermittent emission up to 20 mA/cm^2 was measured for higher switch voltages. The dependence of emission current on switch voltage, grid dimensions, and extraction voltage will be presented.
[S0003-6951(00)01311-5]

Studies of Relativistic Backward Wave Oscillator Operation in the Cross-Excitation Regime

F. Hegeler, M. Partridge, E. Schamiloglu, and C.T. Abdallah
Department of Electrical and Computer Engineering
University of New Mexico
Albuquerque, NM 87131
fhegeler@eece.unm.edu

Abstract

We first reported the operation of a relativistic backward wave oscillator (BWO) in the so-called "cross-excitation" regime in 1998. This instability, whose general properties were predicted earlier through numerical studies, resulted from the use of a particularly shallow rippled-wall waveguide (slow wave structure – SWS) that was installed in an experiment to diagnose pulse shortening in a long pulse electron beam-driven high power microwave (HPM) source. This SWS was necessary to accommodate laser interferometry measurements along the SWS during the course of microwave generation. Since those early experiments we have studied this regime in greater detail. We have invoked time-frequency analysis, the smoothed-pseudo Wigner-Ville distribution in particular, to interpret the heterodyned signals of the radiated power measurements. These recent results are consistent with earlier theoretical predictions for the onset and voltage scaling for this instability. This article presents data for a relativistic BWO operating in the single frequency regime for two axial modes, operating in the cross-excitation regime, and discusses the interpretation of the data, as well as the methodology used for its analysis. Although operation in the cross-excitation regime is typically avoided due to its poorer efficiency, it may prove useful for future HPM effects studies.

Keywords:

Relativistic BWO, High Power Microwaves, Joint Time-Frequency Analysis, Cross-Excitation Instablity, Mode Competition.

Presented at the 24th Infrared and Millimeter Wave Conference, Monterey, September, 1999

Detection of Superluminal (but Causal) Group Velocity in One-Dimensional Photonic Crystals Using a High Power Microwave Source

E. Schamiloglu, M. Mojahedi,* F. Hegeler, G.T. Park, K. Agi,* and K.J. Malloy*

Department of Electrical and Computer Engineering, and
**Center for High Technology Materials*
University of New Mexico
Albuquerque, NM 87131, U.S.A.

Abstract

A novel time-domain experiment was performed utilizing a high power backward wave oscillator to generate a wave packet whose interaction with the stop band of a one-dimensional photonic crystal (1DPC) was studied. A companion wave packet propagating in free space was observed to arrive measurably later in time than the wave packet incident onto the 1DPC. This result is consistent with special relativity and causality since the frontal velocity of the signal never exceeds the speed of light in vacuum.

X-BAND RESISTIVE SENSORS FOR SHORT HIGH-POWER MICROWAVE PULSE MONITORING

M. Dagys[1], Ž. Kancleris[1], R. Simniškis[1], E. Schamiloglu[2], F.J. Agee[3]

[1] Semiconductor Physics Institute, A. Goštauto 11, Vilnius, 2600, Lithuania
e-mail: dagys@uj.pfi.lt
[2] University of New Mexico, EECE Department, Albuquerque, NM 87131, USA
e-mail: edl@eece.unm.edu
[3] Air Force Office of Scientific Research, AFOSR/NE, 801 N. Randolph St., Arlington, VA 22203, USA
e-mail: jack.agee@afosr.af.mil

Abstract – We propose to use a resistive sensor for nanosecond duration high-power microwave pulse monitoring. The designed sensor is sufficiently fast to measure nanosecond duration microwave pulses, can directly handle microwave pulse power up to 70 kW and outputs the signal up to a few tens of volts without any amplification.

Experimental studies of the cross-excitation instability in a relativistic backward wave oscillator

F. Hegeler, M. Partridge, E. Schamiloglu[1], C.T. Abdallah, and N. Islam

Department of Electrical and Computer Engineering
University of New Mexico
Albuquerque, NM 87131

ABSTRACT

Our group first reported the operation of a relativistic backward wave oscillator (BWO) in the so-called "cross-excitation" regime in 1998. This instability, whose general properties were predicted earlier through numerical studies, was a consequence of using a particularly shallow rippled-wall waveguide (slow wave structure – SWS) that was installed in the experiment to diagnose pulse shortening in a long pulse electron beam-driven high power microwave (HPM) source. This particular SWS was required to accommodate laser interferometry measurements during the course of microwave generation. Since those early experiments we have further studied this regime in greater detail using two different SWS lengths. We have invoked time-frequency analysis, the smoothed-pseudo Wigner-Ville distribution in particular, to interpret the heterodyned signals of the radiated power measurements. These recent results are consistent with earlier theoretical predictions for the onset, voltage scaling, and general behavior for this instability. This paper presents data for a relativistic BWO operating in the single frequency regime for two axial modes, operating in the cross-excitation regime, and discusses the interpretation of the data, as well as the methodology used for its analysis. Although operation in the cross-excitation regime is typically avoided due to its poorer efficiency, we discuss how it may be exploited in HPM effects studies.

Keywords: relativistic BWO, high power microwaves, joint time-frequency analysis, cross-excitation instablity, mode competition

RO1 6 Use of a High Power Microwave Source to Detect Superluminal Group Velocities* MOHAMMAD MOJAHEDI,[†] *University of New Mexico* KEVIN MALLOY,[‡] *University of New Mexico* EDL SCHAMILOGLU,[§] *University of New Mexico* FRANK HEGELER,[‖] *University of New Mexico* GREGORY PARK, *University of New Mexico* A novel time-domain experiment was performed utilizing a high power microwave source to generate a short pulse wave packet whose interaction with the stop band of a one-dimensional photonic crystal (1DPC) was studied. A Sinus-6 electron beam accelerator was used to drive a backward oscillator which generated 100s MW peak power at 9.68 GHz (Δf = 100 MHz) in a 10 ns pulse. The microwave pulse generated from this frequency-agile source was tuned to coincide with the mid-bandgap of a 1DPC consisting of alternating layers of polycarbonate and air. This set-up emulated a wave packet tunneling through a photonic barrier. It is observed that the wave packet group velocity is 2.4 c, where c is the speed of light in vacuum. This apparent anomaly does not contradict Einstein causality since the frontal velocity never exceeds c. Details of this experiment and its implications are presented. In addition, some frequency domain results will also be presented.

*This work supported in part by grants from ARO and AFOSR/MURI.

[†]Center for High Technology Materials
[‡]Center for High Technology Materials
[§]Department of Electrical and Computer Engineering
[‖]Department of Electrical and Computer Engineering

UP1 27 Analysis of the Cross-Excitation Instability in a Relativistic Backward Wave Oscillator* EDL SCHAMILOGLU,† *University of New Mexico* FRANK HEGELER,‡ *University of New Mexico* CHAOUKI ABDALLAH,§ *University of New Mexico* MICHAEL PARTRIDGE,‖ *University of New Mexico* The cross-excitation instability in a relativistic backward wave oscillator (BWO) was first observed by our group in 1998.[1] This instability resulted from the use of a particularly shallow rippled-wall waveguide that we had installed in our experiment to accomodate laser interferometry measurements during the course of microwave generation in a high power BWO. Since those early experiments we have analyzed a considerable amount of data to better understand this operating regime. We have invoked joint time-frequency analysis as well as wavelets to interpret the heterodyned signals of the radiated power measurements. We will discuss the interpretation of the data, as well as the methodology used to analyze the data. [1] C. Grabowski, E. Schamiloglu, C.T. Abdallah, and F. Hegeler, "Observation of the cross-excitation instability in a relativistic backward wave oscillator," Phys. Plasmas 5, 3490 (1998).

*This work supported by an AFOSR/MURI grant.
†Department of Electrical and Computer Engineering
‡Department of Electrical and Computer Engineering
§Department of Electrical and Computer Engineering
‖Department of Electrical and Computer Engineering

Overview of Intense Beam-Driven Relativistic Backward Wave Oscillators and their Use in High Power Microwave Effects Studies*

E. Schamiloglu, F. Hegeler, C.T. Abdallah, K. Hahn, and S. Choi
Department of Electrical and Computer Engineering
University of New Mexico, Albuquerque, NM 87131

A great deal has been learned regarding the operation of intense relativistic electron beam-driven backward wave oscillators (BWO's) over the last few years. The issue of pulse shortening seems to be better understood, although its complete remediation has yet to be demonstrated. The energies radiated in X-band have yet to reach the kiloJoule level, although reliable operation at 10's to 100's of Joules has been established.

Recent results achieved at the University of New Mexico [1] have established that it is possible to operate a long pulse intense beam-driven BWO in the so-called "Cross-Excitation" regime in a controlled manner. By this we mean that, by appropriately setting the diode voltage for a fixed slow wave structure, one can demonstrate operation in one of two adjacent axial modes, or operation when the two axial modes are beating for period of time on the order of 10 ns.

In this presentation, we will describe recent results obtained on the long pulse BWO using a variety of sophisticated diagnostics. We discuss operation in the cross-excitation regime, and how it can be exploited in high power microwave (HPM) effects studies.

[1] F. Hegeler, M. Partridge, E. Schamiloglu, and C.T. Abdallah, "Studies of Relativistic Backward Wave Oscillator Operation in the Cross-Excitation Regime," (submitted to the IEEE Trans. Plasma Sci., Special Issue on High Power Microwave Generation).

* This work is supported by an AFOSR/DOD MURI Grant.

Euro Electromagnetics
30 May - 2 June 2000, Edinburgh

7.1

Envelope Power Sensors for HPM Measurement

Dagys, M[1]*; Kancleris, Z*[1]*; Simniskis, R*[1]*; Schamiloglu, E*[2]*; Agee, F J*[3]
[1]*Semiconductor Physics Institute, Lithuania;* [2]*University of New Mexico, USA;* [3]*AFOSR/NE, USA*

Microwave pulses generated by HPM sources are, as a rule, non-rectangular. Therefore, the concept of a pulse's power - the power averaged over the pulse width - is not totally satisfactory to distinguish them. The power envelope or the instantaneous power allows one to more precisely characterize the generated pulses. When measuring the envelope power the averaging time is finite and limited. On the one hand, it must be small compared to the pulse length, on the other, the averaging time must be large in comparison with 1/f, where f is a carrier frequency of the microwave pulse. The response time of the particular device used for microwave pulse power measurement practically limits the minimal averaging time when measuring the power envelope.

In this contribution a series of waveguide type resistive sensors (RS) for HPM pulse measurement with short response time is presented. The performance of the RS is based on an electron heating effect in semiconductors. The sensing element is actually a resistor made from n-type Si with Ohmic contacts on the ends. It is placed within a waveguide where the HPM signal propagates. The HPM electric field heats the electrons in the volume of the semiconductor and its resistance increases. So, by measuring this resistance change the HPM pulse power can be determined. Electron heating inertia is the physical reason that limits the response time of the RS. It is a very fast process with a characteristic time of 2.9·10-12 s for n-type Si at room temperature. Nevertheless, the actual response time of the sensor is limited by the current rise time in the DC circuit of the RS.

The RS for L, S, C, X, Ku and Ka-bands have been designed, manufactured, and calibrated. A 50 V DC pulse supply has been used for the RS feeding so that an output signal of a few tens of Volts has been obtained at maximum power level without any amplification. The response time of the RS has been estimated using a time-domain reflectometry method to be less than 10/f.

The RS has been tested under operational conditions at HPM facilities in the USA. The tests have revealed some advantages of the RS over traditional devices. They can detect directly about 60 dB greater pulsed microwave power, are resistant to larger power overloads, produce high output signals, and are sufficiently fast to measure the power envelope of nanosecond duration HPM pulses.

EUROEM 2000

Euro Electromagnetics
30 May - 2 June 2000, Edinburgh

1.1

An Overview of Recent Advances in Intense Beam-Driven Relativistic Backward Wave Oscillators and Their Use in High Power Microwave Effects Studies

Schamiloglu, E[1]; *Hegeler, F*[1]; *Adballah, C T*[1]; *Christodoulou, C G*[1]
[1]*University of New Mexico, USA*

Much progress has been recently made regarding the understanding of the operation of intense relativistic electron beam-driven backward wave oscillators (BWO's). The issue of pulse shortening seems to be better understood, although its remediation has yet to be demonstrated. The energies radiated in X-band have yet to reliably reach the kiloJoule level, although operation at 10's to 100's of Joules has been established.

Recent results achieved at the University of New Mexico (F. Hegeler, M. Partridge, E. Schamiloglu, and C.T. Abdallah, "Studies of Relativistic Backward Wave Oscillator Operation in the Cross-Excitation Regime," submitted to the IEEE Trans. Plasma Sci. Special Issue on High Power Microwave Geneartion) have established that it is possible to operate a long pulse BWO in the so-called "Cross-Excitation" regime in a controlled manner. By this we mean that, by appropriately setting the diode voltage for a fixed impedance and for a fixed slow wave structure, one can demonstrate single mode operation in one of two adjacent axial modes, or operation when the two modes co-exist and compete for a period of time on the order of 10 ns.

In this presentation we review recent advances in the operation of intense beam-driven BWO's. We present increased understanding obtained through the use of sophisticated diagnostics, as well as novel experiments. We describe BWO operation in the cross-excitation regime and discuss intriguing possibilities on how this can be exploited for HPM effects studies.

Long Pulse, High Power, Large-Orbit, Coaxial Gyrotron Oscillator Experiments

R.L. Jaynes, R.M. Gilgenbach, C.W. Peters, W.E. Cohen, M.R. Lopez, Y.Y. Lau, W.J. Williams, and Thomas A. Spencer*
Intense Energy Beam Interaction Laboratory,
University of Michigan, Ann Arbor MI 48109-2104
* Air Force Research Lab, Phillips Site

Abstract

Long-pulse, large-orbit, coaxial gyrotrons are currently under investigation. The electron beam is generated by MELBA (Michigan Electron Long Beam Accelerator) with parameters: V = -0.8 MV, $I_{anode} < \sim 4$ kA, $I_{tube} = 0.2$-2 kA, and pulselength = 0.5-1 ms. Large-orbit, axis-encircling electron beams are generated by a magnetic cusp. Experimental gyrotron performance with coaxial cavities (unslotted and slotted) is compared to a non-coaxial cavity. The coaxial gyrotron demonstrated superior current transport and microwave production over the non-coaxial gyrotron. The coaxial rod apparently raises the limiting electron beam current in the diode, allowing higher currents to be extracted. The unslotted, coaxial gyrotron showed microwave power levels of 20-40 MW with pulselengths of 10-40 ns. This coaxial gyrotron operated in two main modes: TE_{111} and TE_{112} with frequencies of 2.34 and 2.5 GHz respectively. The gyrotron frequency is tunable between the respective modes by changing the magnetic field. The slotted, coaxial gyrotron showed the highest power of 60-90 MW and extremely short pulselengths of 10-15 ns. For all three gyrotrons, the microwave pulse-shortening mechanisms of mode hopping and mode competition are definitively identified by time-frequency-analysis of heterodyned microwave data.

PHYSICS OF PLASMAS VOLUME 7. NUMBER 2 FEBRUARY 2000

Effects of an external magnetic field, and of oblique radio-frequency electric fields on multipactor discharge on a dielectric

A. Valfells, L. K. Ang, Y. Y. Lau, and R. M. Gilgenbach
Department of Nuclear Engineering and Radiological Sciences, University of Michigan, Ann Arbor, Michigan 48109-2104

(Received 4 June 1999; accepted 27 October 1999)

This paper analyzes, separately, the effects of an external magnetic field, the rf magnetic field, and of an oblique rf electric field, on multipactor discharge on a dielectric. Using Monte Carlo simulation, we obtain the susceptibility diagram in terms of the magnetic field, the rf electric field, and the dc charging field for various dielectric materials. We find that a magnetic field parallel to either the rf electric field or the dc electric field does not qualitatively change the susceptibility diagram. However, an external magnetic field perpendicular to both the rf electric field and the dc electric field can significantly affect the susceptibility diagram. Thus oriented magnetic fields lower the upper susceptibility bound when the magnetic field strength is approximately equal to $B_{\mathrm{res}}[T] = 0.036f(\mathrm{GHz})$, where f is the rf frequency. Both the lower and upper susceptibility boundary may be raised significantly by a large external magnetic field, $B \gg B_{\mathrm{res}}$. Susceptibility to single surface multipactor is greatest when the rf electric field is nearly parallel to the dielectric, but is dramatically decreased for angles of obliqueness greater than approximately $5°-10°$. The rf magnetic field does not affect the lower boundary, but may extend the upper boundary greatly. [S1070-664X(00)03002-0]

41ST Annual Meeting of the APS Division of Plasma Physics, Nov. 15-19, SEATTLE, WA abstracts published in Bull. Am. Phys. Soc. vol. 44, No. 7, Nov. 1999

17:00

RO1 16 Resonant absorption of a short-pulse laser in a doped dielectric* L. K. ANG,† Y. Y. LAU, R. M. GILGENBACH, B. QI, *University of Michigan, Ann Arbor, MI 48109-2104* A simple model is used to calculate the energy absorption efficiency when a laser of short pulselength impinges on a dielectric slab that is doped with an impurity with a resonant line at the laser frequency[1]. This model may be used to determine the proper amount of photosensitive chemicals in photoresists, when various lithography wavelengths (e.g. 436, 365, 248, 193 nm, etc) are used. It predicts that tens of percent of the laser energy could be absorbed with a modest amount of impurity dopant over a wide range of parameters. This enhanced absorption is due to the overlap of dopant resonance spectrum and the laser spectrum. The model shows that maximum energy absorption efficiency is obtained by adjusting the laser pulselength at a given dopant concentration, or by adjusting the dopant concentration at a given laser pulselength. The optimal pulselength may be of the order 100s optical cycles, typical of ultrafast lasers and modern free electron lasers. Dimensionless parameters are constructed, allowing calculation with one set of parameters be used to infer the results for other sets of parameters.

*Supported by NSF, DOE, and AFOSR/MURI
†Present address: Los Alamos National Laboratory

[1]L. K. Ang et al., Appl. Phys. Lett. 74, 2912 (1999); L. K. Ang, Ph.D Thesis, U. Michigan, Ann Arbor (1999)

41ST Annual Meeting of the APS Division of Plasma Physics, Nov. 15-19, SEATTLE, WA abstracts published in Bull. Am. Phys. Soc. vol. 44, No. 7, Nov. 1999

UP1 11 Plasma Processing and Optical Emission Spectroscopy in High Power Microwave Pulse Shortening Experiments*
W.E. COHEN, R.M. GILGENBACH, R.L. JAYNES, C.W. PETERS, M.R. LOPEZ, J.I. RINTAMAKI,† Y.Y. LAU, *Nuc. Eng. and Rad. Sciences, U. of Michigan* T.A. SPENCER, *AFRL Phillips Site*
Mechanisms of pulse shortening are being investigated with a multi-megawatt, oxygen-free copper, coaxial gyrotron. Experiments are primarily concerned with plasma production inside the microwave cavity and e-beam collector. This gyrotron operates in the S-band and is driven by the Michigan Electron Long Beam Accelerator (MELBA) at parameters: V= -750 kV, I_{diode}= 6 kA, I_{tube}= 0.8 kA, and pulselengths of 0.5-2.0 μ sec. RF plasma processing is being examined on the coaxial cavity and e-beam collector to determine its effect on the pulse shortening characteristics of this gyrotron device. Plasma H-α line radiation is measured inside the microwave cavity and e-beam collector via fiber optic probes/monochromators and correlated with microwave power and microwave cutoff. The correlation is being measured of premature microwave cutoff to a rapid increase of H-α optical emission. A strong correlation would suggest that the plasma is cutting off the microwaves as the plasma reaches critical density ($\sim 8\text{x}10^{10}\ cm^{-3}$).

*Research supported by AFOSR-MURI program contracted through Texas Tech U. and by AFRL Phillips Site, Northrop Grumman Corp., and AASERT/AFOSR

†FES Graduate Fellowship, Currently employed by GE Lighting

41ST Annual Meeting of the APS Division of Plasma Physics, Nov. 15-19, SEATTLE, WA abstracts published in Bull. Am. Phys. Soc. vol. 44, No. 7, Nov. 1999

UP1 12 Comparison of Slotted and Unslotted Multi-MW Large-Orbit, Axis Encircling, Coaxial Gyrotron Oscillators*
R.L. JAYNES, R.M. GILGENBACH, C.W. PETERS, W.E. COHEN, M.R. LOPEZ, J.M. HOCHMAN, Y.Y. LAU, *Nuc. Eng. and Rad. Sciences, U. of Michigan* T.A. SPENCER, *AFRL Phillips Site*
Slotted and unslotted large orbit coaxial gyrotrons are currently under investigation with microwave power up to 40 MW. Slotted cavities provide better mode selectivity, which has the potential to reduce problems due to mode competition and mode hopping. In the unslotted cavity, both the TE111 mode at 2.3 GHz and the TE112 mode at 2.5 GHz are observed, while in the slotted cavity, the TE112 is the dominant mode. The axis encircling electron beam is generated by a magnetic cusp field. Current transport through the magnetic cusp and through the microwave cavity are examined. The electron beam is produced by MELBA (Michigan Electron Long Beam Accelerator) with the following parameters: $V= 0.75\text{-}1.0$ MV, $I_{diode}= 1\text{-}10$ kA, $I_{tube}= 0.2\text{-}1.5$ kA, pulselength$= 0.5\text{-}1.0\ \mu$ sec.

*Research supported by AFOSR-MURI program contracted through Texas Tech U. and by AFRL Phillips Site and Northrop Grumman Corp.

41ST Annual Meeting of the APS Division of Plasma Physics, Nov. 15-19, SEATTLE, WA abstracts published in Bull. Am. Phys. Soc. vol. 44, No. 7, Nov. 1999

UP1 14 Time-Frequency Analysis of High Power Microwaves Using Discrete Prolate Spherical Sequences* C.W. PETERS, R.M. GILGENBACH, W.J. WILLIAMS,[1] Y.Y. LAU, R.L. JAYNES, W.E. COHEN, M.R. LOPEZ, *Nuc. Eng. and Rad. Sciences, U. of Michigan* T.A. SPENCER, *AFRL Phillips Site* Time-Frequency analysis has been performed on heterodyned, S-band microwave signals from a large orbit, coaxial gyrotron, revealing characteristics such as microwave frequency modulation due to electron beam voltage fluctuations, mode hopping, and mode competition. However, TFA utilizes the Fourier transform of the local autocorrelation function, resulting in a spectrum with a large variance. The variance can be reduced by using discrete prolate spherical sequences (DPSS). Another advantage of DPSS is the development of a large, wide main lobe, placing spectral energy around the actual frequencies. Noisy signals with a signal-to-noise ratio of 0 dB have been successfully tested utilizing DPSS.

*Research supported by AFOSR-MURI program contracted through Texas Tech U. and by AFRL Phillips Site and Northrop Grumman Corp.

[1]Department of Electrical Eng. and Computer Science, University of Michigan

41ST Annual Meeting of the APS Division of Plasma Physics, Nov. 15-19, SEATTLE, WA abstracts published in Bull. Am. Phys. Soc. vol. 44, No. 7, Nov. 1999

UP1 36 Effects of Magnetic Fields, and of Oblique RF Electric Fields on Susceptibility to Multipactor Discharge on a Dielectric* A. VALFELLS, L. K. ANG,[†] Y. Y. LAU, R. M. GILGENBACH, *University of Michigan, Ann Arbor, MI 48109-2104* We analyze, separately, the effects of an external magnetic field, the RF magnetic field, and of an oblique RF electric field, on the susceptibility of a dielectric to single surface multipactor. Using Monte Carlo simulation, we obtain the susceptibility diagram in terms of the magnetic field, the RF electric field, RF frequency, and the DC charging field for various dielectric materials. We find that a magnetic field parallel to either the RF or the DC electric field has only a minor effect on the susceptibility diagram. However, an external magnetic field perpendicular to both the RF electric field and the DC electric field can significantly alter the susceptibility diagram. Thus oriented magnetic fields lower the upper susceptibility bound when the field strength is approximately equal to Bres [T] = 0.036 f [GHz]. Both boundaries of the susceptibility region may be raised appreciably by a large external magnetic field, $B \gg Bres$. The RF magnetic field is found to have negligible effect upon the lower susceptibility boundary, but may extend the upper boundary greatly. We find that susceptibility to single surface multipactor is greatest when the RF electric field is nearly parallel to the dielectric, but is dramatically decreased when the angle between the RF electric field and the dielectric surface exceeds 5 - 10 degrees.

*Supported by DOE and AFOSR/MURI
[†]Present address: Los Alamos National Laboratory

41ST Annual Meeting of the APS Division of Plasma Physics, Nov. 15-19, SEATTLE, WA abstracts published in Bull. Am. Phys. Soc. vol. 44, No. 7, Nov. 1999

UP1 37 Multipactor Discharge and RF Window Failure* REX ANDERSON, A. VALFELLS, L. K. ANG,†Y. Y. LAU, R. M. GILGENBACH, *University of Michigan, Ann Arbor, MI 48109-2104* J. VERBONCOEUR, *UC Berkeley* A. NEUBER, H. KROMPHOLZ, *Texas Tech University* We report our ongoing effort on single surface multipactor discharge on a dielectric. In our previous work, using a zero-D Monte Carlo model, we construct susceptibility diagrams for various dielectric materials, and predict that about 1 percent of the RF power is deposited on the dielectric, via the multipactor discharge, over a wide range of conditions[1]. Here, we report our latest results obtained from the PIC-code, XOOPIC[2], which accounts for two dimensional effects, and in particular, the various effects of space charge. The simulation results will be compared with our previous models[3]. We also present a preliminary analysis on outgassing from the dielectric and subsequent plasma formation, due to the multipactoring electrons, as the next step toward window failure.

*Supported by AFOSR/MURI and DoE
†Present address: Los Alamos National Laboratory

[1]Ang et al., IEEE Trans. Plasma Sci. 26, 290 (1998)
[2]Verboncoeur et al., Comput. Phys. Commun. 87, 199 (1995)
[3]Ref. [3] and Neuber et al., J. Appl. Phys. (in press, 1999)

MICROWAVE BEAM-DRIVEN PROPULSION EXPERIMENTS FOR HIGH-SPEED SPACE EXPLORATION

James Benford*
Microwave Sciences Inc.
1041 Los Arabis Lane, Lafayette, CA 94549 USA

Henry Harris
Advanced Projects Group, Jet Propulsion Laboratory,
4800 Oak Grove Dr., Pasadena CA 91109 USA

Gregory Benford
Abbenford, Inc,
1105 Skyline Dr., Laguna Beach, 92651 CA USA

Timothy Knowles
Energy Science Laboratories Inc.,
6888 Nancy Ridge Dr., San Diego, CA 92121 USA

We are conducting experiments and modeling to demonstrate the technique of using the photon pressure of a directed beam of microwave radiation to propel a sail of ultralight C-C material. In the future, this method can be used to propel probes to very high speeds for science missions to the outer solar system, the interstellar region and the nearby stars.

Beam-driven scientific probes have the advantage that energy is expended only to send the payload and an attached sail in the region of scientific interest, not to accelerate the driving source itself. The beam source remains on Earth or in nearby space, so can be used to launch many such probes. The method has a substantial efficiency advantage over rockets for reaching speeds >100 km/sec.

We report progress of a laboratory exploration to move photon-pushed sails from paper concept to laboratory reality. We are using a 20 kW 7 GHz beam incident in a 10e-7 Torr vacuum chamber on new ultralight carbon-carbon microtruss fiber sails of mass density 1-10 g/m2 at microwave power densities of ~kW/cm2. This should give accelerations of several gees. Sails under such accelerations reach ~2000 K, ruling out most materials. Diagnostics are optical and IR video photography, pyrometer, reflected microwave power and residual gas analysis. A predictive dynamic model of coupled differential equations is compared directly with the measurements.

We also discuss deep space exploration missions and concepts for building the infrastructure for space exploration using beamed microwave power systems.

*Work supported in part by the AFOSR HPM MURI Program.

MICROWAVE BEAM-DRIVEN SAIL FLIGHT EXPERIMENTS

>

>Gregory Benford
>Abbenford, Inc,
>1105 Skyline Dr., Laguna Beach, 92651 CA USA

>James Benford*
>Microwave Sciences Inc.
>1041 Los Arabis Lane, Lafayette, CA 94549 USA

>Henry Harris
>Advanced Projects Group, Jet Propulsion Laboratory,
> 4800 Oak Grove Dr., Pasadena CA 91109 USA

>Timothy Knowles
>Energy Science Laboratories Inc.,
>6888 Nancy Ridge Dr., San Diego, CA 92121 USA

>Keith Goodfellow & Raul Perez
JPL

We have demonstrated flight of ultralight sails of Carbon-Carbon material at several gees acceleration. To propel a sail of ultralight >C-C material we sent a 20 kW, 7 GHz beam into a 10e-6 Torr vacuum chamber and onto sails of mass density 5-10 g/m2. At microwave power densities of >~kW/cm2 we saw upward accelerations of several gees and flights of up to 60 cm. Sails so accelerated reached >2000 ¡K, a capability of carbon which rules out most materials for such high acceleration missions. Diagnostics were optical and IR video photography, pyrometer, reflected microwave power and residual gas analysis. A predictive dynamic model of coupled differential equations compares well with the measurements. In the future, this method can be used to propel probes to very high speeds for science missions to the outer solar system, the interstellar region and the nearby stars.

*Work supported in part by the AFOSR HPM MURI Program.

FY94 HPM MURI
Central Consortium

TEXAS TECH
UNIVERSITY

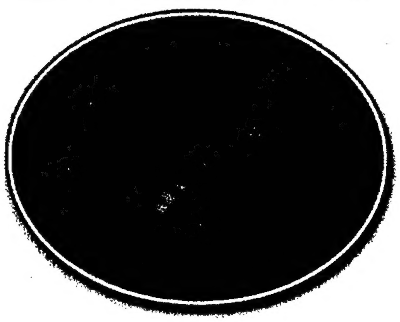
The University of New Mexico

microwave
sciences

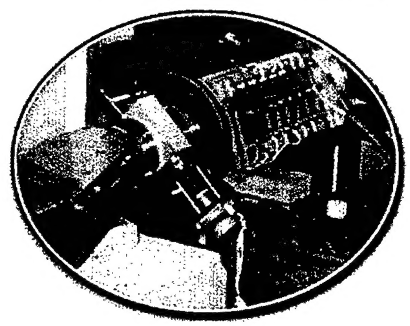
objective

To investigate new approaches for HPM generation with longer pulse lengths and greater efficiencies in order to make HPM weapons systems practical.

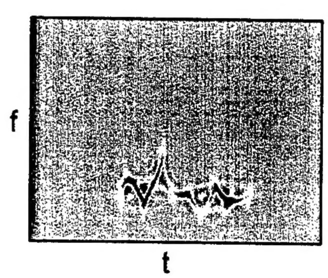
Identified pulse shortening mechanisms



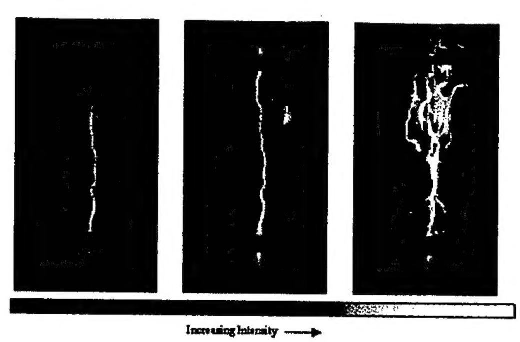
Invented Gigawatt-level "Smart Tube"



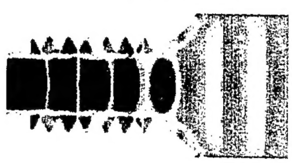
Time-frequency analysis of HPM sources



Revolutionized the understanding of window breakdown



IEEE Press Book
Advances in High Power Microwave Sources and Technologies



Edited by R.J. Barker and
E. Schamiloglu, IEEE Press, 2001

Numerous transitions to AFRL